MULTI-DISCIPLINARY SOCIO-TECHNICAL MANAGEMENT: INTEGRATING ROBOT TECHNOLOGY AND MANAGEMENT ISSUES

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Abstract: Optimal integrated design is potentially the most significant consequence of recent advances in service robotic technologies, enabling novel organizational forms to evolve. This paper provides a broad vision of the advent of a novel multi-disciplinary organizational function in the manufacturing and service sectors. Socio-technical management means an appreciation of the interplay among technology, economic issues and human factors. This allows an extended range of economic feasibility for robotic applications that also enables a more humane work organization. Contemporary trends are reviewed. Anticipated changes in operation and work organization are discussed, indicating a new robotic era.

Keywords: robotics, technological management, industrial engineering, automation and socio-economic issues, work and organizational design, organizational effectiveness

1 INTRODUCTION

The accelerating technical development of intelligent self-regulating robotic systems poses new challenges. Anyone who plans to work and live in the world of tomorrow needs to pay attention to how the situation might change and what the implication of these changes might be. The transformation that we are able to witness today will hopefully change our society for the better:

> The processes that shape our technologies go right to the heart of the way in which we live and organize societies. Understanding these processes might help us to create different or better technologies … It shapes our conduct at work and at home. It affects our health, the ways in which we consume, how we interact, and the methods by which we exercise control over others. [1]

The entry into the robotic era, with automated intelligent systems will play a decisive role in the transformation of management during the years and decades ahead. From this vantage point the missing element becomes evident; multifarious knowledge of complex socio-technical systems will be needed for optimal operation. This involves a much higher level of complexity of coordination and control in order to make the interlinked and often vulnerable systems more functional. Hence, this kind of management involves the interplay between many different knowledge areas and will accordingly require more extensive skills as well as a deeper understanding of systemic aspects.

Recent breakthroughs in service robotic technologies have gradually enabled more sophisticated forms of interaction between humans and robots. Robots are designed to interact with people in different contexts and environments. Earlier types of industrial robots have basically been dependent on relatively primitive interaction techniques, such as hand-controller, buttons, and graphical interfaces. Modern interactive robots enable more sophisticated interaction, such as communication with higher-level commands, including voice and gesture recognition. [2, 3, 4]

Changes in technology entail changes in values and norms, work roles, and social structures that profoundly alter an organization. Robotic systems are deployed to perform heavy, dirty, dull and repetitive tasks autonomously in order to relieve the strain on humans. Possibly, in our future daily world more advanced types of service robots will be conceived as work partners [3]. This transformation from lifeless artifacts to cooperative, interactive, and mobile partners (functioning as team members) enables new forms of synergies with humans.

Sophisticated automated robotic systems however, will not be enough to ensure corporate survival. We must not forget the socio-technical and economical dimensions which are crucial for the adaptive and innovative performance in business. Robotic technology is a resource created for human purposes that must serve human, organizational and economical objectives.

In today's business, decision-making is complex and demanding. The survival of the manufacturing firm is hazardous in a complex world increasingly variable, unpredictable, and fraught with fatal risks. Therefore, its mobilization of multifarious competencies is becoming crucial. However, this complexity requires a holistic understanding (i.e. a general understanding of the total system, that is, a rough knowledge of its parts and how they interact) in order that management can make sound decisions and bridge communication gaps. For this very reason, the socio-technical aspect is fundamentally important for business enterprises. This paper addresses concepts of human intelligence, economical objectives, and automated robotic technologies which working together and optimized will enable novel organizational forms to develop.

2 THE ORIGINS OF MANAGEMENT

The origins of modern management can be traced back thousands of years [5]. However, the organized development of management theory is commonly considered from the nineteenth century with the emergence of large industrial organizations, and consequent problems associated with their working conditions. 'Management' has been used as a concept of divide and conquer. It has also perennially sought its leadership models from the military organization, regarding business as a battlefield and stressing the organization of formal hierarchical relationships.

However, it is useful to recall that the practice of management and its relationship to military organization has far more historical antecedents. Pioneering organizational theorists and management thinkers, such as Frederick Taylor and Henry Fayol, were widely acknowledged in Europe and Japan at the time of the "machine age", while receiving only moderate recognition in their home countries [6, 7]. All the leading thinkers were at that time vigorously involved in the improvement of management as a means of increasing industrial productivity, a perennial theme of management.

2.1 Management as a science

The father of modern forms of scientific management, Frederick Winslow Taylor (1875-1917), an American inventor and engineer published his concepts in one of his most well known publications entitled "The principles of scientific management" [6]. In Taylor's philosophy, management is based to a large extent on a number of practical guidelines. In particular, management gives detailed instructions to employees what tasks to perform. In this sense, management is imposed upon people, rather then together with people. Taylor's philosophy based on meticulous observations and methodological analysis of the best way how a specific task could be undertaken and completed. A large amount of industrial operations and body movements were accurately studied and registered that enabled analysis of every aspect of the work process. Having found the optimal procedure, employees then were instructed to apply it in a mechanical manner.

To fully understand Taylor's philosophy it must be placed in its rightful context. He lived and worked when mass production techniques, mechanization and industrialization were initially evolving. Taylor's ideas have largely been discarded and disparaged in modern management. Nevertheless, it is possible to notice Taylor's influence on the re-engineering movement, associated with breaking down business processes into constituents.

2.2 The socio-technical systems paradigm

The principal notion of traditional socio-technical theory is the concept of "boundary management", which implies a high degree of self-regulation throughout the organizational system [8, 10, 19]. Flexibility and adaptability is obtained through a general repertoire of complementary human skills, possessed by semi-autonomous groups. However, the idea of separate approaches to the social and the technical systems of an organization could no longer be sufficient. The proper technology is the one that best fits the total circumstances [9]. Studies of mechanization and automation "… *disclosed a basic change in the core shop-floor tasks: the worker was outside the technology, adjusting, interpreting, monitoring, etc: he had become a manager of a work system: he needed conceptual and perceptual skills rather than manipulative and physical skills – to keep a complex system in a steady state*" [10].

Nadel, classified institutions into *regulative* or *operative*. The former approach treats organizations exclusively as social systems, stressing cultural values and norms. The latter deals with material resources as organizational outputs [11]. Soon after Emery adapted Nadel's distinction, restricting the term 'socio-technical' to the operative institution [9]. The distinctive characteristic of such an operative organization is a wide-ranging interface that "*consists of the relations between a non-human system and a human system*" [10].

Previous investigations suggested that technology might influence managerial functions. Woodward's study [13] suggested that technology determines the organizational design. Fewer supervisors were found in continuous process than in mass production industries. It was suggested that the highest level of technological complexity occurs when a continuous process industry is mechanized and demands sophisticated feedback in the form of adaptive systems.

Von Bertalanffy's classic paper on "*Open Systems in Physics and Biology*" [12] became a source of influence at the time when the socio-technical movement began to evolve. Conceptually, it entailed a new view on how organizations were envisaged. By means of adopting the notion and metaphor of "open systems" organizations like organisms and machines needed to uphold a steady state (homeostasis).

3. MODERN MANAGEMENT IN TRANSFORMATION

3.1 From mechanization to automation

In today's industrial and service organizations we are able to witness an increasing automation, which is a natural extension of the previous mechanization. Automation of machines concerns replacement of human's sensory organs and intellectual abilities by these machines [14, 15, 17, 18].

In automated machines, the human function is to monitor the process and detect malfunctions. Hence, it is merely supervising the construction processes and detecting deviations that need to be corrected. This has increased effectiveness and productivity in operations. Improved operation productivity, interpreted in the broadest sense, has become a survival issue for many organizations. Therefore, socio-technical management must acquire multi-disciplinary knowledge in order to be able to realize objectives of effective operations. Socio-technical management means an appreciation of the interplay of technology, business and human factors.

3.2 From functional specialization to universalism

In the machine age a leader was a professional, who considered organizations as closed systems. Such a single specialization model has dominated business thinking since the turn of the twentieth century. This paper, in contrast, does not assert single specialty but rather a multi-disciplinary management function. In the period of accelerated development of sophisticated technology, paradoxically, leadership competencies like corporate social responsibility and ethics will become increasingly decisive for the overall result and survival of the corporation.

4. MULTI-DISCIPLINARY MANAGEMENT SKILLS IN THE ROBOTIC ERA

4.1 Social skills

There will be a need for totally new integrated competencies for leading simultaneously both human and technological systems since these systems are becoming more complex in their interactivity. Managers with good social skills are able to get the best out of their people. Development of new work forms in the robotic era must consider human needs of *meaningfulness*, *purpose* and *engagement* for the optimization of performance of the combined system. Psychosocial considerations and initiatives to humane working environments in the service sector address the associated risk of social isolation.

4.2 Technological skills

Technical competence involves the knowledge and collection of behaviors that one can bring to productive completion of tasks. Technology cannot be separated from its social inputs. It must be integrated into business contexts that make full use of the knowledge, originality, and ingenuity of the human resources available. Hence, the high-performance construction worksite is a design that brings together technical, social, and economical subsystems in a manner that optimizes the correlation among them in order to produce effective operations. Robot systems will execute some of the work. According to Engelhardt and Edwards "*The division of labor between the intelligent human and the smart system can be examined and optimized. In this way both the human and the machine can perform the portions of the task which each does best.*" [16]

4.3 Economic and managerial skills

Management, on the other hand mainly involves the knowledge of efficiency, planning, regulation, control, and stability. When effectively acquired and integrated, these social and managerial competencies will jointly establish a high-performance holistic organization. The concept of socio-technical management also implies important elements of decentralization, information transfer, steering, and control. Significant improvements of productivity can be achieved if the work is carried out without space and time limitations, for example, tele-operation of robotic systems in a virtual environment.

The traditional service sector approached the organization exclusively as a social system and management as the act of governing social processes. The robotic service systems, currently under development will however offer many different services in the future reflecting the change from the industrial to the service society.

5. CONCLUSION

Intelligent technologies, such as novel and innovative robotic systems will make the high-performance operations of manufacturing and service business a fundamental driving force in the twenty-first century. A major concern in the present state of development is the replacement of the traditional functional specialization model that has dominated business thinking since the turn of the twentieth century. This paper, in contrast, does not assert single specialty but rather a multi-disciplinary management.

During the previous era, Frederick W. Taylor developed principles of scientific management. A philosophy of specialization that progressed into the field of industrial engineering and also laid the groundwork of organizational theory. These principles served business well for several decades but today's situation calls for other thoughts. The restrictions become even more evident in light of sophisticated automated robotic applications.

There are various implications of this paper for practicing managers and engineers. Managers need to take more cognizance of the interaction of economic, socio-political and technical aspects. There is a need for new holistic multi-disciplinary management education to raise the awareness of this situation. Therefore, managers could more readily understand and live with the uncertainty and ambiguity that is now so prevalent in modern management operation.

Thus, a novel multi-disciplinary business function that integrates both human intelligence, economic objectives and automated robot technology becomes increasingly important in the robotic era. In-depth grasp of the underlying foundations of these three elements of socio-technical management, and a vivid commitment to sustain them, are fundamental for optimization of automated robotic technologies. Therefore, the relation among these three factors should be the object of attention in future research. I contend that the multi-disciplinary socio-technical management function is indeed a concept that is essential for economic growth, competitiveness, increased efficiency and operational productivity in a global world.

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Proposal for Applying Telematics Concept and Analyzing Economical Model in Site

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Abstract: Nowadays, the dependence of productivity on construction equipment is getting bigger and the mass of equipment cost is increase, those are indirect evidence of important of equipment. But construction field has the characteristic that is the various activities and wide work area. These make many problems in the operating of equipments. These problems bring about diminution of workability and productivity, in result it makes increase of cost and time. Owing to solve the problems, this study introduce of Telematics. This study analyzes process into its work and management for construction equipment using at the land work, and will apply Telematics to the field equipments.

Keywords: Construction equipment, Telematics, Site characteristic, Economical analysis model

1. Introduction

1.1 Background and Object

Today, construction business is considered as a typical 3D industry and shows higher separation rate than other businesses, and at the same time the age of people engaged in construction industry is getting older and older. Accordingly, construction equipments which have been radically introduced since 1980's become substantial element as a supplement for insufficient labor power in construction field and the dependency upon construction equipment at site is getting higher and higher.[1]

Yet the improvement are required because there is limit in making the best use of productivity of construction equipment along with the difficulty in managing process related to construction equipment due to the feature of construction equipment and construction site.

In this study, I would like to examine and analyze the management situation regarding construction equipment at construction site, propose the management concept of construction equipment applied Telematics which can lead to the productivity improvement, enumerate the expected effect and propose improvement plan based upon the existing model taking economic feature into account.

1.2 Scope and Methodology

In this study, I intend to conduct research on the site management of construction equipment and concept of Telematics through literature inquiry, find the problem in managing construction equipment at construction site and factor which influences on productivity, and search for improvement plan for this problem through the interview with site manager and construction equipment operator.

Through this study, I plan to forecast the improvement effect in case of applying Telematics in return for earth work used excavator, dump truck, bulldozer, etc., indicate elements which should be considered for analysis of economic feature and propose improvement plan based upon suitable concept regarding the analysis model of economic feature among the existing researches.

2. Telematics

2.1 Definition of Telematics

Telematics is a composed word of Telecommunication and Informatics and variously defined, but in general it means consolidated service which combines GPS technology, wireless communication technology, system which enables user to have interactive communication, etc., and provides vehicle and driver with diverse information and service.[2]

Recently, Telematics is being brought into relief and mainly used in automobile industry thanks to the Ubiquitous, which is epochal paradigm and the development in wireless and mobile communication technology.

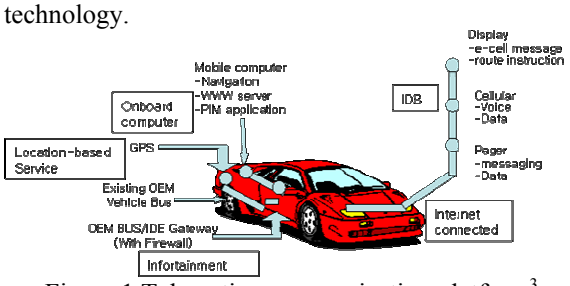

Figure 1 Telematics communication platform[3]

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2.2 *Function and Using of Telematics*

The service provided by Telematics technology can be found via the feature of Telematics in automobile industry. Based on its use purpose, Telematics is classified as

1)Service related to traffic information, navigation and operation, etc.

2)Service related to safety, protection, diagnosis, troubleshooting, etc.

3)Service related to entertainment, private information, communication, etc.[4]

Telematics service provides the driver with dealing with car accident, theft, road information, living information, etc. at real-time and can provide tailored service for individual drivers using mobile communication technology and global positioning system by means of terminator installed in vehicle.

Service Type		Fucntions
Traffic Information	Road Service	Traffic information, Navigation,
	Management Service	Self-inspection, Checking reservation , Quality management
Safe, Self-Test,	Office Service	Internet connection, Mobile image meeting, private business conduct, etc.
	Emergency Service	Emergency connection, Medical service, emergency measure, etc.
	m-Commerce Service	Electronic commerce base on mobile network
	Extra Service	Burglary prevention, Remote Control
Entertainment	Delivery service	Information of delivered productivity, Stock management, Customer management
	Entertainment Service	Movies, On-line game, etc.

Table 1 Telematics service[5]

Moreover, it can check the status of major parts and inform repairman of accurate malfunctioning point and reason through the embedded computer.

	USA	W.Europe	Japan
Market characteristic	-Homogeneous market -Large land mass -Spotty wireless coverage -many network operators	-Multiple language -Multiple culture -Inter-country trip -Cell phone & SMS use	-Homogeneous market -Difficult navigation -Long-term ITS Vision -Packed-based cell phone
Focus	-Safety&security -Concierge -Content & LBS	-Safety&security -Mobility portals -Traffic/Routing /Navi	-Navigation -Real-time traffic info. -Mobilit/Travel/ POI
Platform approach	-Embedded solution -simple interface	-Embedded solution -simple interface -Mobile devices	-Navigation system -Coupled with phone adapter -New platforms emerging
Issues	-Driver distraction -Privacy protection	-Fragmented market -Language barriers	-What's next after navigation? -Carwings,G-book?

Table 2 Regional Telematics Difference[6]

Lately more and more local and overseas companies are using Telematics but its applicable method depends on countries. In Korea, there was a service which had similar concept to it through the linkage between communication company and automobile company in the past yet the actual service using the name of Telematics has been provided these days.

2.3 *Forecast of Telemaics*

Telematics is expected to have more features owing to the development in relevant technology. In particular, the rapid development in computer and communication technology and getting cheaper price might be considered as a factor which makes Telematics market active. Eventually, Telematics is expected to grow fast based on many domestic/international factors. Especially since Telematics has been designated as promising industry for next generation recently in Korea, not only aggressive research but also rapid development as to related technology are expected.

Computer H/W & peripherals	Mobile Communication	Multi media Tech.
Micro Processor	GSM, PDC, CDMA, TDMA	Digital Compaction (MPEG)
Memor(Flash)	2.5G/3G Cellular	DSP
CD/DVD	Digital Radio(DAB, DVB, DSR)	3D Acoustic
Speech Recognition	LAN	Display(LCD, HUD)
Speech Convertor	Ku/Ka Satellite	High Speed Data Bus
Access(xDSL, Cable, Wireless)	Bluetooth	Conditional Access
High Speed Internet	WAP/WML	Smart Card
Router		DVD/MP3 Playback

Table 3 Technologies related in Telematics[7]

3. Operation of Construction Equipment in Site

I planned to examine and analyze the process from work order to work completion in finding management problem in construction equipment at construction site. Generalized management process of construction equipment through the interview is as follows.

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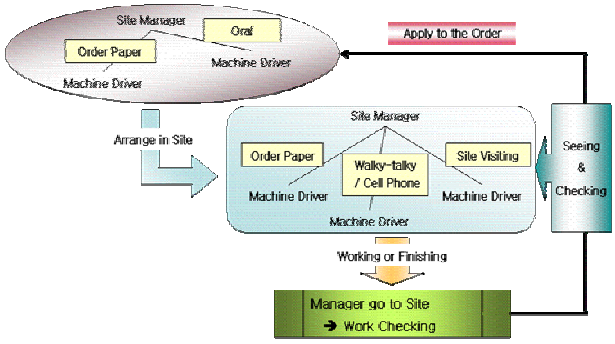

Figure 2 Construction equipment existing operation

It takes more than 1 hour a day on an average for site manager to move for the tasks related to construction equipment like work order, work confirmation, etc. and more than 2 hours to prepare for move and other works related to construction equipment out of entire work hours.

3.1 Characteristic of Construction Site

It is difficult to completely understand site situation because various process are conducted at various external spots in most of construction works. Particular, in case of public work site, the site manage should spend his/her major time moving because the area is broad and he/she must confirm works moving from places to places. This makes his/her time for other works decreased, incidentally provokes expense increase in fuel and maintenance and distracts the problem from being settled fast in case of long distance. In addition, site manager has difficulty in effectively getting information because the works are carried out at many places and this is limitary factor in systemic management of site information.

3.2 Characteristic of Construction Equipment

The space for operating construction equipment is narrow, the impact in using it is directly conveyed to operator's body and this can deteriorate work efficiency. Moreover, most of works are simple and iterative, working site is far from site office or it has the restriction although it is close and this can make the construction equipment operator feel isolated in case of log-term work. Unlike common worker, construction equipment operator is required to do additional process like equipment warming-up, supply to fuel, oil replacement, grease infusion, etc. for maintenance and he/she should check various things while operating devices as a construction equipment operator. This needs additional time than common worker.

3.3 Complex Characteristic

Complex feature of site and equipment related to the management of construction equipment has influence on transmission/modification of work, process status, confirmation of result, etc.

Task	Task Contents	processing method
task ordering	Work scope delivering Changed scope delivering	Tranmit directly (face to face) Using of walkie-talkie or cell phone
task confirming	Work progress checking Work completion checking	Using of walkie-talkie or cell phone Confirming directly (by naked eye)
outbreak dealing	Problem solving (Demend decision of the site manager)	Using of walkie-talkie or cell phone Confirming directly (by naked eye)

Table 4 Work related on construction equipment

In case of face to face meeting for work performance or using communication means like handie talkie, mobile, etc. he/she must stop working due to noise from equipment or restriction in operating it. This means the reduction in working hours and can affect productivity.

3.4 Analysis of Earth-work

Earth works is a general term for work which is dealing with soil such as excavation, load, conveyance, heaping, etc. in construction works and fundamental process in most of construction.

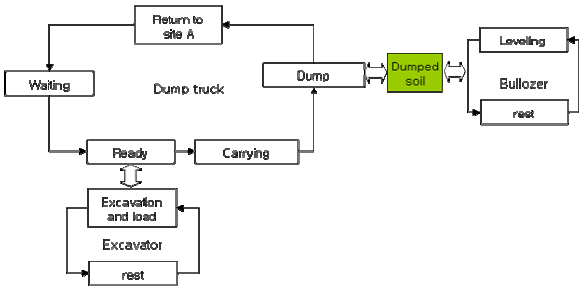

Figure 3 Earth work flow

Thus, price reduction in work can also influence on overall works through productivity improvement in earth works. Equipment related to earth works can be selected considering the rule of equipment combination along with workload, conveyance distance in carrying soil, road status, etc.
In this study, I intend to search for applicable field for Telematics and apply it based on works like excavation by shovel, loading soil, conveying soil by truck, leveling process using bulldogger, etc.

4. Application of Telematics in Site

The work that Telematics can be applied at construction site is a process which can reflect the feature of Telematics, and GPS technology, image/voice data, sensing technology, etc. are applicable, and it can be applied to earth works.

4.1 Using of GPS

In earth works, since dump truck secedes from site and moves for soil delivery, shovel which loads soil and bulldogger which level soil are likely to stop doing process unless the truck reaches working place. It is difficult to find its location while dump truck in the process of move. However in case of GPS installation, it is easy to find the location of truck and this enables user to effectively know control of work speed, addition to further equipment, etc. In case of GPS installation in shovel and bulldogger, it ensures more convenient work process management via the analysis of working pattern of equipment.
In addition, surveying process can be minimized in existing works because leveling status can be known in leveling works through application of GPS technology.

4.2 Using of Various Data

Currently, site order can be classified, which is site manager delivers process order document before the commencement of works and oral order by face to face meeting. Site manger and construction equipment operator should spend more time than common worker for process order because process order must be completed before starting works. According to the information from interview, construction equipment operator spends approximately 30 minutes more than common workers to reach the site and receive works and site manager spends more than 1 hour to be ready for work and move for process order.
In case Telematics is applied, site manager can order works by transferring various data like image, voice, character, etc., which are suitable for each process at site office. It is expected that site manager can reduce move, operator can receive correct process order. In case of problem in works, manager must consume more than 30 minutes to visit site, on the other hand, in case Telematics is applied, site status can be monitored via installed camera in equipment and relevant settlement can be transmitted in many ways.

4.3 Using of Sensing Technology

Construction equipment is required to be continuously managed for effective works. Additional process is needed like warming-up, fuel check, diverse oil check, grease infusion, making management document, etc. On the whole, the construction equipment operator is conducting these process using before/after work, lunchtime, etc. and it takes 1/2~1 hour for them. In comparison with common worker under application of work commencement/completion, decisively it means decrease in working hours or break as compared with common worker because the construction equipment operator should use time except for working hours like break. If Telematics is applied, warming-up using remote control is available via sensing technology and embedded computer in equipment, the equipment itself notifies problem in case of problem after automatic fuel and oil check and can do basic settlement. Equipment check card and history card are handled as a electronic document and pertinent matters can be solved by minimizing construction equipment operator's concern. This is expected to save time for work preparation and equipment maintenance.

4.4 Using of Others

It is hard for construction equipment operator to leave site and handle private things like common worker. In case of using internet connection service provided by Telematics, he/she is forecasted to deal with his/her personal business. If he/she use the existing communication means, he/she should stop working due to its inconvenient operation, on the contrary in case of using voice communication feature of Telematics, he/she is expected to effectively use his/her working hours by minimizing its influence due to communication.
Conclusively, the improvement in productivity and minimization of operation time for equipment will be able to be realized via the application of Telematics through the improvement in working environment for construction equipment operator. At the same time, information created during work process automatically is converted into DB and effective productivity management will be able to come true together with information management through linkage with legacy systems PMIS, KMS in the future.

Before Telematics introduction	After Telematics introduction
A movement and explanation time requirement for the task instruction	The alternate to the transmission of a relation information
The limit for the task explanation of means	Using the various data (voice, video, etc.)
A movement time requirement for the task checking	The monitoring in the spot office

Table 5 The expectation effectiveness(Site manager)

Before Telematics introduction	After Telematics introduction
A time need the maintenance and management the construction equipment	The minimize through the practical use of a sensing technique of the task
Restricted task information transmit	Using the various and efficient data
Efficient utility of a task hour difficulty	Efficient task environment supply
The limit due to a equipment control of the understanding	Smooth understanding supply

Table 6 The expectation effectiveness (Equipment operator)

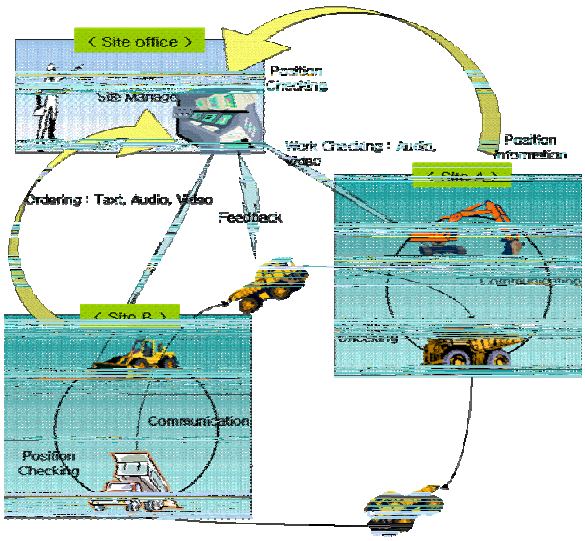

Figure 4. Telematics applied earth work

5. Consideration for Feasibility Analysis of Teleamtics

5.1 Consideration for Feasibility Analysis

The factors which must be considered to improve economic feature in applying Telematics are initial investment cost for system implementation, labor cost reduction owing to system implementation, anticipated cost for productivity improvement due to increased working hours.
Anticipated cost may be vary from what surplus time will be converted into work among the uncertain considered factors for the analysis of economic feature, thus it is difficult to measure the cost correctly because it has not been applied. I deem this problem should be resolved through the constant study in the future.

	Append elements	Utility purpose	note
Construction Equipment	Wireless camera	Site checking	Escaping & sticking /fix cost
	DGPS transmitter & receiver	Equipment position checking Amount of work checking	Escaping & sticking /fix cost
	Terminal unit	-Visualization of work	Escaping & sticking /fix cost
	Modem	Data transmitting and receiving	Escaping & sticking /fix cost
	Sensors	Amount of work sensing Eequipment condition checking	Fix /fix cost
	Input&output equipments	Data input & output	Escaping & sticking /fix cost
Site Office	DB Server	Site DB saving	Fix /fix cost
	Modem	Data transmitting and receiving	Escaping & sticking /fix cost
	System operating software	System operating	Fix cost
	Equipment management program	Equipment management	Fix cost
others	System manager	System management & operating	Labor cost /regular cost
	Cost of communication & data using	Communication line using	Regular cost
	Installation cost	Equipments installation	Fix cost

Table 7 Clear consideration for economical analysis

the charge computation is possible	Foreman cost	The minimize of role of equipment foreman through the central management of equipment
	Assistance cost	The minimize of role of equipment assistance through the equipment management system
	Surveying cost	A charge degrade from the automation and minimize of the survey
	Visiting cost	A vehicle carrying and fuel cost reduction through minimizing of the number to visit the site directly.
the charge computation is impossible	Expectation cost	The expectation cost which minimize of the site visiting and switching other work
	Reduction of equipment management time	The expectation charge from the enlargement of a main task time through the minimize of an equipment officer hour
	Work time increasing	The expectation charge from the enlargement of the task time

Table 8 Vague consideration for economical analysis

5.2 Feasibility Forecasting Model

In order that the application of Telematics to construction site may carry conviction, its economic feasibility should be proved. To analyze economic feature of Teleamtics application, we should prove whether reduction effect cost gained via system introduction within applicable period for application model is bigger than cost invested for model configuration. In this study, I would like to propose analysis model of economic feature which is suitable for Telematics as a reflective model among existing analysis models of economic feature based on economic feasibility analysis model concerning existing Hume pipe laying automation device.[8] Because I consider this is a device for productivity improvement, connects existing equipment with additional equipment, minimizes other processing time and it is similar to the concept of this research. Economic feasibility analysis model regarding Hume pipe laying automation device is as follows.

[8] Kim K.T, Han J.G, Lee J.B, Han C.H, Development of an Economic Feasibility Forecasting Model for Introducing Teleoperated Pipe Manipulator, Architectural Institute of Korea vol 22, 2002. 10

$$I \le \frac{L \times C \times D - (M + O + S)}{1 + i} + \frac{L \times C \times D \times (1 + j) - (M + O + S) \times (1 + \alpha)}{(1 + i)^2} + \cdots\cdots + \frac{L \times C \times D \times (1 + j)^{n-1} - (M + O + S) \times (1 + \alpha)^{n-1}}{(1 + i)^n} = \sum_{k=0}^{n} \frac{L \times C \times D \times (1 + j)^{k-1} - (M + O + S) \times (1 + \alpha)^{k-1}}{(1 + i)^k} = \frac{L \times C \times D}{i - j}\left[1 - \left(\frac{1 + j}{1 + i}\right)^n\right] - \frac{(M + O + S)}{i - \alpha}\left[1 - \left(\frac{1 + \alpha}{1 + i}\right)^n\right] \quad (1)$$

Here is,
I : Initial investment cost for pipe laying automation device
L : Decreased labors to use automation device
C : Labor cost per man
D : No. of work-days per year
M : Maintenance cost of automation device
O : Operation cost of automation device
S : Moving and others cost
i : Interest rate j : Labor cost increase rate
α : Inflation per year
n : Fixed period of automation device

In applying equation(1) to this concept of Telematics, the factor which must be additionally considered is the generated opportunity cost when needed time for existing additional process is converted into other process in case of applying Telematics to construction equipment. The following result can be shown in case of applying this to equation (1)

$$I \le \frac{(L \times C_1 \times D + T \times C_2)}{i - j}\left[1 - \left(\frac{1 + j}{1 + i}\right)^n\right] - \frac{(M + O + S)}{i - \alpha}\left[1 - \left(\frac{1 + \alpha}{1 + i}\right)^n\right] \quad (2)$$

Here is,
I : Initial investment cost for Telematics
L : Decreased labors to use of Telematics
C_1 : Labor cost per man
T : Time of Conversion from original works to other works per day
C_2 : Expectation cost per hour
D : No. of work-days equipments applied Telematics per year
M : Maintenance cost of equipments applied Telematics
O : Operation cost of equipments applied Telematics
S : Moving and others cost
i : Interest rate j : Labor cost increase rate
α : Inflation per year
n : Fixed period of equipments applied Telematics

6. Conclusions and Future Studies

In case of applying Telematics system to construction site, site manager can manage time effectively and overall improvement in productivity is expected to be realized. Moreover, construction equipment operator is forecasted to improve working efficiency and entire productivity based on the improvement in working environment.
In this study, I intended to consider factors in applying Telematics system to the site and examine feasibility analysis model by summarizing the necessary factor in considering economic feature via previous interview with construction site manager and worker.
In case of applying Telematics to the site, site manager is expected to perform confirmation/order of work effectively, reduce the time in moving to the site and shift into other works. At the same time construction equipment operator is forecasted to minimize maintenance of construction equipment, reduce unnecessary time for actual work and use his/her time effectively through overall improvement in working environment.
At the next step, the feasibility consideration in applying Telematics is required in case of applying proposed economic feature model to the site in this study.

Acknowledgement

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NOWADAYS TRENDS IN ROBOTICS AND AUTOMATION IN CONSTRUCTION INDUSTRY: TRANSITION FROM HARD TO SOFT ROBOTICS

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Abstract: The actual research trends in robotics and automation in construction industry (RAC) are much different in comparison with the last decade. While during the 90s the R&D activities were focused in the development of new robotic systems (most of them teleoperated) and in existing machinery automation, the actual efforts are concentrated more in the software integration, sensory data acquisition and processing, safety and secure systems, sensor-based process control and construction industrialization. This paper deals with the short state-of-the-art in the actual and features RAC research areas, including representative examples.

Keywords: Automation, hard and soft robotics, civil infrastructures, house building, research trends.

1 INTRODUCTION

The construction industry is one of the most unfamiliar R&D fields in the robotics and automation community. Nevertheless the construction industry is one of the oldest and largest economic sectors. The construction industry's contribution to the GDP in industrialized countries is about 7-10%. In the US this contribution rises to 12% and in the EU there are about 2.7 M enterprises (most of them SME) involving in the business. This data is comparable with manufacturing industry but with double investment in R&D for manufacturing.

During the old ages the technological level of construction industry was very high for their historical period. The old civilizations build very long lasting structures like pyramids, acropolis, aqueducts, cathedrals, etc. They used innovative processes and elements. Nevertheless, nowadays some construction processes change not so much. For example, the building erection process has changed very little over the past eighty years. The middle ages pulleys are substituted by cranes. They are more sophisticated than centuries ago, but work with the same philosophy: manual control, human operator visual feedback, big positioning error, etc. The only elements that have change are: the actuators (electrical motors instead of human force) and materials (steel based instead of wood). These two advances permit to increase the elevation speed, payload and reachability. But construction philosophy is not changed a great deal.

In the field of service robotics the construction industry is one of the most important areas of research. The main difficulty of RAC is related with on-site out-door environment's conditions that are very unstructured. The manipulation of heavy pieces, big tolerances, low level of standardization, medium level of industrialization and pre-fabrication, intervention of numerous non-coordinated actors (architects, builders, suppliers, etc.), etc. are others important features of this sector. This is why all the involved actors (researchers, companies and administrations) must make new efforts to increase the automation level of this important sector.

During the 90s the R&D activities in the field of RAC were leadered by Japanese companies and universities, and were focusing in the development of new robotic systems (most of them teleoperated) and in existing machinery automation. This era of the RAC research is called *hard robotics* [1]. These robots tried to automate several construction processes in the house building and the civil construction. These robots were for interior building finishing, brick layer masonry, modular industrialized building's construction, road paver's sensor-based guidance, excavator's control, infrastructure inspection, tunnel and bridge construction, etc.

The "bubble economy" crisis en Japan and created overexpectation of the RAC strongly reduced investment in research activities during the last 3-4 years. Only few construction robots had success in the market. Nevertheless, the situation is changing now and new research RAC trends have been launching. The actual R&D activities are centring more in the *soft robotics*. It defines not as software only but also as hardware, but not in the machinery sense. It includes on-site sensory data acquisition and processing, human operator's field safety and security, chip-based process control, etc

2 HARD ROBOTICS STATE-of-the-ART

The main research activities of the RAC in the past decade were divided accordingly to applications into two large groups: civil infrastructure and house building [2]. Typical civil infrastructure robot applications are the automation of road, tunnel and bridge construction, earthwork, etc. In the group of house construction, main applications include building skeleton erection and assembly, concrete compaction, interior finishing, etc. Classification according to applications is consistent with other possible classifications, which divide RAC R&D activities according to the development of new equipment and processes or the adaptation of existing machinery to transform them into robotic system.

In this section several examples of the so called hard robotics are presented. In the group of civil infrastructure the examples are road pavers' sensor-based guidance, earthmoving control and infrastructure inspection. In the group of housing the examples are interior building finishing, brick layer masonry, column welding, modular industrialized building's construction.

2.1 Civil infrastructures

In the field of road construction, several projects had been developed over the last decade. They were mainly focused in the development of the new generation of semi-autonomous road pavers and asphalt compactors. The EU projects CIRC [3] and latter OSYRIS (www.osyris.org) had as the main objectives, based in the GPS and laser data, the semi-autonomous guidance of the machines and the quality control of pavers and roller processes by controlling the speed, temperature, layer thickness, travelled distance, etc. (Fig. 1). The coordination of several machines in order to improve productivity is also the objective of the project.

Figure 1. OSYRIS project sensor-based compactor.

In the field of earthwork the research is centred in the introduction of new control techniques to existing machinery like excavators, bulldozers, draglines, etc. One of the major exponents of this research area is the control by CSIRO of the 100-m tall walking crane used in surface coal mining [4]. The swing cycle of the dragline accounts for about 80 percent of time taken. The automatic swing cycle improves the efficiency of the machine, taking in mind that the bucket which weighs around 40 tonnes when empty and up to 120 tonnes when full, acts as a large pendulum and requires operator skill to control well (Fig. 2). The torque-force control during the excavation is also improving the productivity of the processes. The University of Sydney project [5] developed an automated excavator that accounts for interaction forces in analysing the required bucket motion therefore seems promising. As the bucket comes in contact with its environment, the contact force must be regulated such that it remains within a specific range by using specific intelligent control strategy (Fig. 3).

Figure 2. CSIRO's dragline project.

Figure 3. University of Sidney's automated excavator.

The periodic inspection and maintenance of the civil infrastructures was another important research activity. The inspection of building skeletons, complex roofs, off-shore platforms, bridges, etc. represents an extensive and valuable field of work. It is estimated that in the EU there are over 42.000 steel

bridges with a replacement cost of 350 M€. The ROMA family climbing robots [6] able to travel in a complex 3D environment carry out several inspection sensors (laser telemeters, colour cameras) in order to transmit the field data to the "ground" system (Fig. 4). The key issue of these robots is the grasping method (grippers, electromagnets, suction cups, etc.) and the robot's adaptive control taking in mind gravity forces.

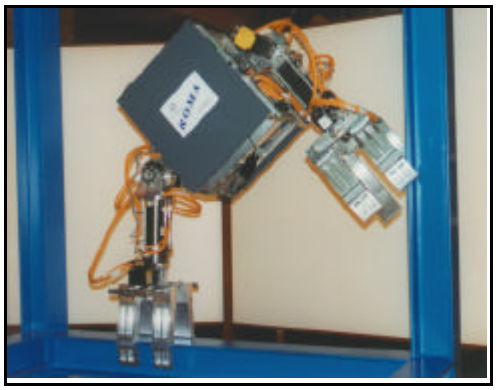


Figure 4. ROMA climbing inspection robot.

2.2 House building

Interior-finishing operations in the building are very time consuming and requires high degree of accuracy. There are several mobile manipulators able to perform variety of operations like extend, compact and control the thickness of the floor concrete, painting and steel column fire protection spraying, assembly of interior walls and ceilings, etc. Most of these robots are teloperated and perform only simple operations. The most representatives' robots of this type are Japanese ones. Two examples are presented: the "Mighty Hand" robot from Kajima (www.kajima.co.jp), which lifts heavy elements in construction as concrete walls, etc. (Fig. 5), and the SurfRobo from Takenaka (www.takenaka.co.jp), which automatically compact the concrete floor by using two sets of rotary floats (Fig. 6).

Figure 5. Kajima's interior wall assembly robot.

Figure 6. Takenaka's concrete compactor robot.

Several robots for automatic assembly of buildings were developed in the past. The effort had been done in the brick layer masonry. The EU project ROCCO developed a large-range (10 m reach) and high payload (up to 500 kg) hydraulic 6 DOF robot for brick assembly [7]. The robot is equipped with auto-tracking laser telemeter in the tip in order to perform prices (up to 5 cm) brick assembly. In this way the control system avoid important arm flexion. The robot performs the assembly sequence obtained by the planning software and needs an initialization process in order to know the bricks pallet position (Fig. 7).

Figure 7. ROCCO project brick assembly robot

The assembly of steel-based buildings is performing by welding, such as column-to-column and column-to-beam joints. The Japanese WR mobile robot performs a variety of column-to-column welding (Fig. 8). The columns can be of up to 100 mm in thickness and round-, square-, and H-shaped steel pipes, as well as box-sectional members. For column-to-beam welding, there is a combination welder/transport type which can run on decks and a type which can weld lower flanges from below.

Figure 8. WR mobile robot for column welding

Automation and robotization of the complete building erection is the most exciting experience. Applying to the high-rise building there were several Japanese projects. The most significant is the SMAT system developed by Shimizu [8]. It was used for construction of more than 30 stories office building. It consists of all-wheatear, full-robotic factory on the top of the building. The lift-up mechanism automatically raises the construction plant and at the same time raises the on-site factory, called *field factory* (Fig. 9). More recently the Dutch companies develop the new whole building erection technology but in opposite way of the previous system. The building is totally constructed in like factory environment and then transported to the final location. The 10 floor building called Bolder was transported by water in a three day operation (Fig.10).

Figure 9. SMART factory in the top of the building.

Figure 10. Bolder building transportation by water

3 SOFT ROBOTICS TRENDS

As it was discussed before, *soft robotics* is not only limited to software itself but also includes other related technology as sensory data acquisition and processing, human operator's field safety and security, chip-based process control, etc. This section describes the main applications and some examples of the actual soft robotics trends. It is important to note that for real RAC applications the *soft robotics* must be balanced with the hard one.

3.1 Software integration

Software integration in the field of RAC is crucial for implementing the concept of the Computer Integrated Construction (CIC). The idea is to integrate in a common exchange format all the stages of the construction, i.e. from architect's desk and planning tools to site robots. The EU FutureHome projects develop the AUTOMOD3 system (Fig. 11) that integrates in a common CAD environment several tools like design, planning and automatic robot and machine programming [9]. Due the high level of conservatism of building designers, the main idea is to use the common 2D architectural design (drawings) and automatically transform it into 3D drawings. In this way it is possible to perform also automatically the modularization of the traditionally designed buildings. This process permits to industrialize the house-building by modular pre-fabricated construction.

Schedule management software packages are used more and more in construction. Nevertheless, its dynamic integration whit all the actors participate in the construction is not yet done. In a construction project, although the completion day is clearly decided, construction schedule is often changed by the weather or the actual progress situation of the project. When a difference arise between present

state and the master schedule, it is necessary to adjust the construction schedule and to execute it immediately. The communication with part's produced factory, transport agents, stores and other suppliers is performing in real-time and in automatic way [10].

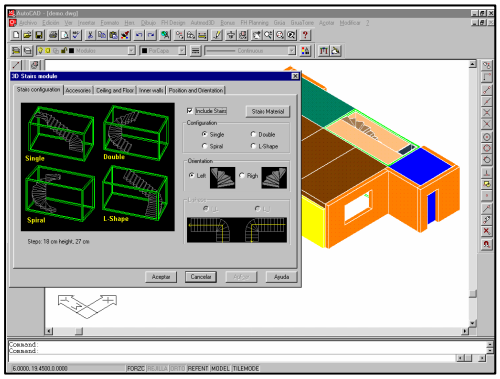


Figure 11. FutureHome integrated design and planning tools.

Mobile computing systems for data transfer between constructor managers and different web-sites have been implementing. The progress monitoring wireless mobile system permits to check the progress of the work. At the same time field note system is used to note unacceptable parts of works (Fig. 12). Inspection system is also used for inspect the result of construction. The document management system not only can communicate with the designers DBs in order to download the CAD drawings, but also permits the on-site modifications of these drawings. This soft technology is very useful and has a low cost which make them candidate for massive introduction in the site environment. The day when construction managers and operators carry only some paper drawings will be finished soon.

Figure 12. PDA-based document management system in the site environment.

3.2 VR systems

The Virtual Reality (VR) software together with an immersive projection display (IPD) allows construction managers to enter and interact with the contents of a full-scale building, before start or during the construction. The virtual mock-up offers first person presence, or the feeling that you're actually in the room when you're just standing in a space bounded by five large screens that surround you with a projected image. The virtual mock-up experience is real enough to enable welders, for example, to crawl under virtual structures and hit their heads on virtual pipes to determine if there's enough room to work. Several immersive VR systems were developed during the last years, like at the Penn State University (http://www.arl.psu.edu), at the NIST (http://cic.nist.gov/vrml/equip.html), etc.

In the world of construction operations analysis, the ability to see a 3D dynamic animation of an operation that has been simulated allows the experts, field personnel, and decision makers can discover differences between the way they understand the operation and the way the model developer understands it. The dynamic VR is more close to animation than geometrical visualization. The actual research is focusing on designing automated, discrete-event process simulation-driven methods to visualize construction operations and the resulting evolving products in dynamic, smooth, continuous, 3D virtual worlds. The discrete-event simulation systems, allows a computer to create a world that is accurate in time and space; and which shows people, machines, and materials interacting as they build constructed facilities.

Using VR system for simulation and training is another *soft robotics* area. For complex machines like excavators, the VR system needs not only to simulate the geometry and kinematics of the machine but also the terrain and the interaction between the machine and terrain [10]. The simulation of digging and driving over the terrain is the crucial test. The terrain model is generated with an elevation grid technique which specifies a height field over a uniform grid. If the size of an individual grid in the simulation is smaller than the footprint of the excavator the system will work correctly and the operator's sensation will be good. The system permits to be inside or outside the excavator cabin. To visually represent the digging process, the location of the bucket relative to the terrain and relative to the excavator needs to be known. To drive a complete *Caterpillar* 3D backshore simulator, please see in the web page http://www.howstuffworks.com/backhoe-loader.htm.

a)

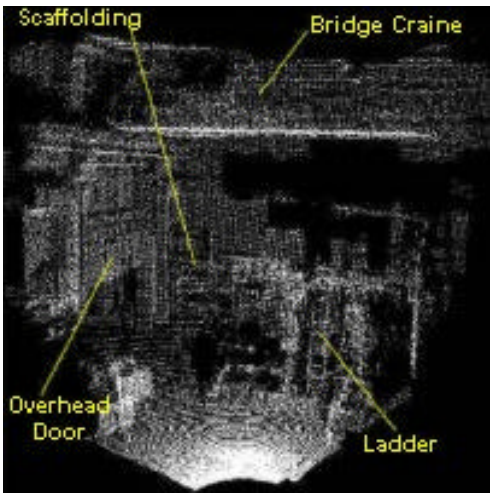
b)

Figure 13. VR environment for excavators training system: a) inside the cabin, b) outside the cabin.

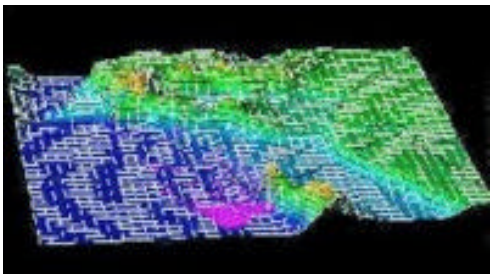
3.3 Sensory data acquisition and processing

One of the most promising are of research in *soft* RAC is the sensory data acquisition and processing. The use of sensor for modelling the environment and then use this data for processing is much valuable for the control of automatic construction machinery or robots. The LADAR (Laser Radar) on-site data acquisition was one of traditional research area at NIST [11]. Nevertheless, only recently this technology has important applications in the automatic excavation, truck guidance, topography and inspection. LADAR technology is based on the high precision pan-and-tilt mounted laser rangefinder with the frame rate at least 10 Hz (commonly 25 Hz). The range of the laser scanner is up to 150 m for objects with reflection coefficient grater than 80% and 50 m for objects with reflection coefficient grater than 10%. Once the data are registered, they are used to generate 3D models or surfaces (Fig. 14).

Evaluation of surface generation algorithms involves a three-part process. In the first part, the characteristics (accuracy, noise, and related uncertainties) of the sensor would be determined. This "calibration" would be performed in an indoor facility, which allows for a controlled environment. In the second part, mathematical procedures are used to determine the statistical uncertainties of particular calculations (e.g., volume) based on the results of the instrument calibration. In the third part, the characteristics of the algorithms used to generate the 3-D model would be determined (how well does it handle missing points, outliers, discontinuities, vertical surfaces, etc.).



a)



b)

Figure 14. NIST's LADAR data: a) environment map, and b) 3D reconstruction

The using of GPS for data collection is become very common. Some applications are very well known as automatic truck guidance, topography, etc. But nowadays low-cost facilities of using PDA-based GPS and web data transmission and collection make possible new applications. One of these applications is the GPS-aided earthquake monitoring. The data is collected via a GPS station with a circular antenna firmly fixed in a 4.5 tonne slab of 300 million year old sandstone from Yorkshire, which is in turn embedded almost three metres into the earth. This natural landmark is monitoring every 15 second via web.

3.4 Safety and secure operation

Thousands of construction workers are injury or killed in construction accidents each year. Some researches are conducting to look into new ways of improving the security and develop methods and reliable systems to detect possible failures and to avoid any harm to the workers, machines and installations. The main risk sources in on-site environment are collision with the machine transporting heavy and big pieces, falling, machine running over, etc.

In this *soft robotics* research, the compulsory safety helmet required for all workers in the site is used as the base to hold miniature positioning and communication instruments (Fig. 15) [12]. Bidirectional voice channel, portable GPS and micro-camera with video link are some of the helmets elements. The position and ID of each worker is communicated periodically via radio link to a monitoring station. These information is compared with a DB containing the tasks and processes to be perform in the site. If a given worker is at what the system considers a hazard source it acts according to the nature of source.

There are two basic secure levels: machine and human ones. Machine level refers to the failures in the machinery, possible erroneous operation, bad condition of the components, etc. As far as the human level is concerned, the objective is to prevent the operatives from suffering the accidents. The strategy to adopt consist in the definition of different safe and prohibited zones around the workers and the sources of danger, so that in the moment in which these areas comes into contact a danger situation is triggered and warning is generated. There are several actions to be done in this situation: advise the worker thought the voice commands, stops the machine movement via central computer, etc.

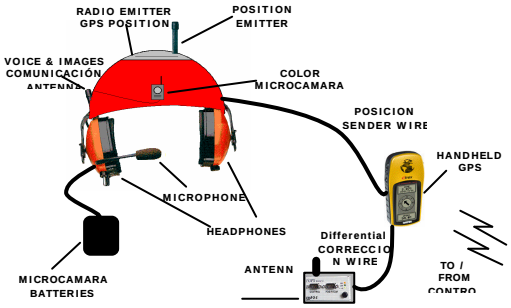


Figure 15. UC3M's active security system elements.

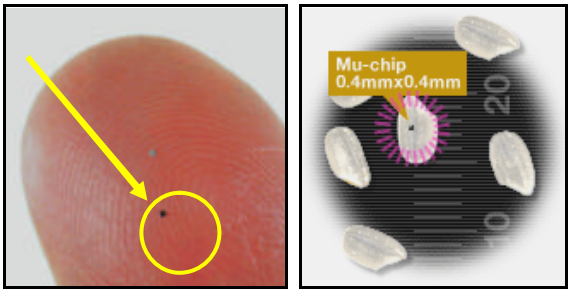
3.5 Part-oriented construction

One of the most innovative soft robotics applications in construction industry is the so called part-oriented construction [13]. The main idea is to link the fixed and temporary facilities of construction site (ground, cranes, field factories, etc.) with the parts-peoples dynamically changing world via information network. It means that the status, position and timing of parts and human operators in the site are known in every moment. Moreover, it is possible to dynamically plan, command, tracking and monitoring all the construction recourses.

To perform this monitoring each part, machine and operator has assigned an identification chip which wireless connects with external devices. This chip is a wireless semiconductor integrated circuit that stores an ID number in its memory (Radio Frequency Identification Device -RFID). The µ-chip developed by Hitachi is a micro-device with square of 0.4 mm that uses the frequency of 2.45GHz. It has a 128-bit ROM for storing unique ID (Fig. 16).

The system which controls whole the construction process is called glue logic. This system binds multiple application software modules, referred as "agents", developed and compiled separately, and coordinates those agents. As "glue logic" supports even notification and conditioning monitoring features based on active data scheme, users can easy build real-time event-driven application agents. The glue logic consists of two major parts: communication subsystem exchanging data with concurrently running agents and the data management subsystem.

Every part has attached µ-chip (which includes antenna). When a chip-implanted part passes through the gate, the gate reads the product URL. It determines what it is, when and in what state it is. The corresponding data point in the glue logic is then altered, which generates an event and a chain of succeeding actions. For communicates with human operators some of them carry a wireless PDA which is capable to connected to the main web server where glue logic is running and, at the same time, is capable to read µ-chip attached to the part. Moreover, the system is applied to automated handling of devices, by communication with automatic cranes and glue logic DB.



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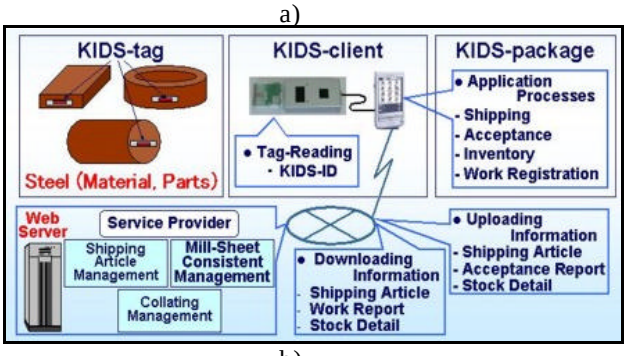

b)

Figure 16. *Hitachi's* RFID µ-chip a) in comparison with the human finger and rise grain, and b) their application for steel-based parts' tracking.

4. CONCLUSIONS

This paper presented the short-state-of-the-art in the area of hard robotics focusing in the new robots development and machine automation. This area was very strong during 90s. But actually it is balanced with the new emerging one called soft robotics. It is based on the software integration, simulation and VR, sensory-based monitoring and tracking, part-oriented construction, etc. These examples are the most representatives but not the unique ones. It is possible to mention other new soft applications like artificial life modelling of the construction process, life cycle engineering, RFID chip-robot interaction, etc.

The RAC's sciences and technology moves actually in the direction to soft robotics. It is not means that hard robotics is end, but their development is actually slowly. Integration and coordination of both hard and soft areas is the objective of the long-term research in the field of RAC. It is very welcoming that this research focus strategically appears in several national and regional research programs, like the EU 6th Frame Program. It is also supported in the inter-regional global program IMS.

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Comparative Study on Supervision System in South Korea and Japan

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Abstract:
Recently, the construction industry is increasingly internationalized. Especially in the Northeast Asian region, there are opportunities in which companies from various countries collaborate in projects more and more. And a lot of problems are caused by the differences between Western project management and local project management.

The aim of this study is, as a part of international comparative study on project management, to clarify the characteristics of the supervision system in South Korea and Japan. In this study, construction management system including related regulations is analyzed. And the differences between construction supervision in Japan and that in South Korea are made clear.

Keyword: supervision, supervisor, construction law, Korea, Japan

1 Introduction

The internationalization of the construction market advances increasingly. Recently, European and American project management (PM) has got into Asian market and friction has been caused. On the other hand, each country in Asia is preparing for the next stage corresponding to the change in the market environment. Therefore, it is necessary to clarify the system of PM in each country which has been performed unconsciously from an objective aspect.

The comparative investigation of the supervision system in South Korea and Japan is discussed in this paper.

2 Contractor's work

2.1 Quality control

The arrangement of engineers (based on the construction industry law) and the preparation of the construction ledger are made as contractor's work concerning the quality control in Japan(based on law concerning the promotion of fair tenders for public construction and proper contracts) And the arrangement of engineers (based on the construction industry fundamental law) and the planning of quality assurance are established in South Korea (based on law concerning management of construction technology). The arrangement of engineers is a commonly-observed feature in both countries, but the preparation of the construction ledger in Japan and the establishment of quality assurance in South Korea are two different things.

The purpose of imposing on contractors the duty for the preparation of the construction ledger is to increase transparency for the parties concerned of layered structure of the organization at the site, especially for clients. Since documents for subcontract are attached to the construction ledger, clients can prevent possible misconduct which might violate the value of the quality of the construction by auditing the ledger.

On the other hand, it is believed that the aim of obligating the establishment of quality assurance plan is to clarify the system of construction quality control for clients as well. Moreover, it should be considered that there is a shade of meaning of showing the framework of contractors' quality assurance plan by prescribing the contents of quality control plan in detail.

The difference between contractors' services reflects the peculiar background of each country. It is said that the construction industry of Japan has developed based on long-term mutual trusts between the clients and contractors. To maintain this mutual trust, contractors have improved their management ability independently, and clients have left work trusting contractors ' ability of management. A long-term relation exists between the main contractors and subcontractors similarly. Contractors in Japan has established the self-management system to control quality centering on major general contractors through such development process.

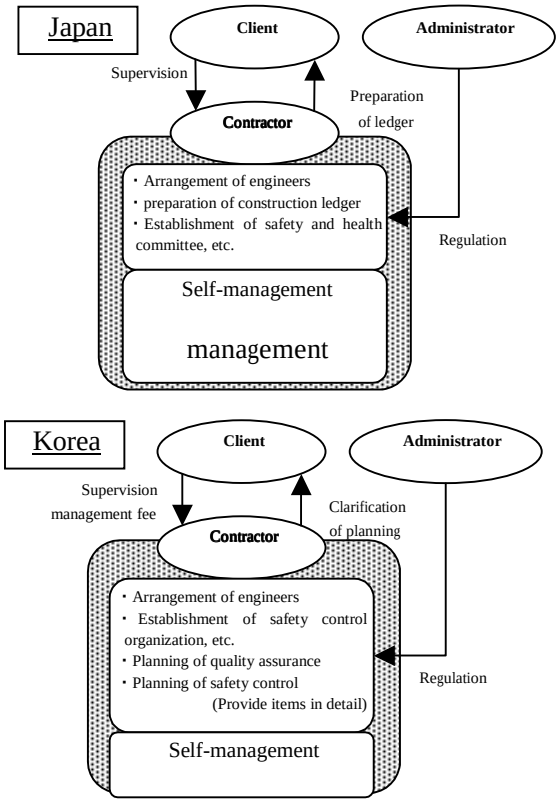


Fig.1 Management in Japan and South Korea by contractor

On the other hand, it is thought that distrust of contractors' self-management ability lead to the foundation of the construction administration in South Korea. It is necessary to compensate for the lack of contractors' ability of management or to correct it for public ends as well as the client. The matter which affects the quality control is established in detail for that.

2.2 Safety management

The work concerning the safety control is to set up the safety and health committee in Japan (based on Industrial Safety and Health Law), and the establishment of the safety control organization (based on law concerning health and safety of industry) and the safety control plan (based on law concerning management of construction technology) in South Korea. A commonly-observed feature in both countries is the establishment of the organization concerning safety control based basically on law covering all industries; occasionally special provision for the construction industry is made because of its layered structure and the complexity on the construction site. Detailed regulations for the safety control are established in Japan as well as South Korea. This is because accidents in the construction industry are more than those of other industries and one of the most important missions of the administration is to protect workers' life. In South Korea, the safety control has been enhanced by providing the establishment of the safety control plan and the content in further detail based on law concerning management of construction technology. It is thought that the lack of the self-management ability of contractors is the cause for the development of safety control as well as the quality control.

3 Comparison of supervision system

3.1 Execution of supervision

The official personnel does the supervision as a supervisor in public construction projects, and the architect who belongs to the architectural firm does in private construction projects in Japan.

The supervision in South Korea is provided by the architect who belongs to the architect office or the supervisor who belongs to the company specialized in the supervision. But, there are buildings which only the registered supervisor can supervise. The supervisor who belongs to the company of the supervision specialty does "Responsibility Supervision". (System of South Korea which obligates clients to consign the supervision to the private supervision specialty company in addition to the supervisor of public organization in public constructions above 10,000,000,000won)

3.2 Legal position of supervisors in construction

(1) Delegation of inspection function from the administration

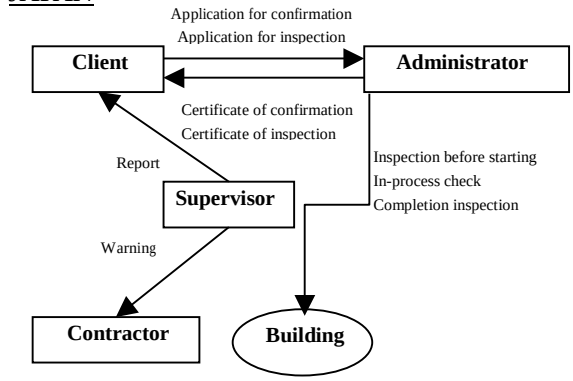
When the construction is completed and the supervision work is ended, supervisors in Japan must report the result to the client in written documents. After receiving the notice of the completion of supervision, the client applies for inspection of the building by the administrative authorities. If the inspection is successful, the client can get the approval for occupation.

In addition to this completion inspection, the authority is conducting in-process check in Japan when specific process which the site manager indicates is completed. It is obligated to submit the management report to the client for the supervisor in South Korea as well as in Japan. However, if the supervision report which the supervisor made is presented, the approval for occupation can be got. In a construction where the supervisor is not

appointed, the supervising authority is supposed to inspect it.

(2) Giving of strong authority

JAPAN



KOREA

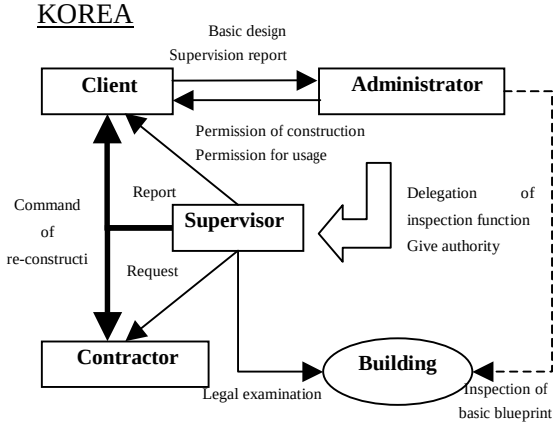


Fig.2 Legal frame of supervisor in construction

The difference between two countries is seen in the actions that should be done by the supervisor in a construction. When a construction turns out to be not executed as described in the drawing and specification in Japan, the supervisor gives advice to the contractor at once. And, if the contractor ignores, if the supervisor is supposed to report the matter to the client. Therefore, it is assumed that the report to the client is supervisor's work. In South Korea, after notifying the client, the supervisor is supposed to request the correction or re-construction to contractor when construction is not being done as the drawing and specification shows.

It is assumed that the work of the supervisor in Japan is nothing more than that. However, in South Korea, when the contractor refuses such requests, cancellation of the construction can be ordered. Not only the contractor but also the client should obey the order. In addition, it is prohibited to take all retaliatory actions against the supervisor who executed the request or order by canceling the appointment or refusing to pay. Thus, a strong power with legal grounds is given to the supervisor in South Korea; supervisor's authority exceeds that of client's.

3.3 Content of the supervision

It is assumed that the legal examination of the drawing and specification is the basic work of the construction supervision. A prior consultation to the drawing and specification and the legal examination of them at the building site are included in the construction supervision.

There is no description about the work of the supervision in the law, but there exists in the consignment book on the construction supervision in Japan. Since construction permission can be obtained only by the examination of the basic drawing and specification in South Korea, the party who can carry out legal examination to a detailed drawing is needed. It seems that in order to have the construction supervision bear a part in this service, the legal examination of the drawing and specification is provided for basic work of the construction supervision.

It is believed that the confirmation of the application form for the approval of use and the examination of the completed drawing of construction are basic work of the “construction supervision”.

The administration or a designated representative of the administration does the completion inspection, and gives the approval of use afterward in Japan. In South Korea, if the completed report of the supervision is sent in as an application document, the approval of use can be gotten. Thus, there is legally a close relation between the approval of use by the administration and the work of the construction supervision.

The examination and guidance of contractor's safety control and quality control are described clearly as work of the “construction supervision”. As for the Japanese construction supervision, the work includes the examination of the construction plan and the management as a supervisor, though the meaning of the “construction plan” is ambiguous. In case of South Korea, the service of the construction supervision is described clearly as the examination and guidance of the contractor's safety control and quality control, and these are the basic work which the construction supervision must do especially in a large-scale construction.

The system of the responsibility management in South Korea is done by stationing the supervisor on the building site. A private supervision company

which is commissioned to do the responsibility management by public organizations should station its supervisor on the building site as the responsibility supervisor.

4 Strength and weakness of management system of Japan and South Korea

4.1 For Japan

The strength of the management system of Japan lies in a close network centered on competent general contractors based on a long-term mutual trusts and cooperative relationship. The soft warily ability like the quality controls and the safety control is accumulated in the close relationship between main contractors and subcontractors, and this has enabled companies to implement the project smoothly. Moreover, the client can take advantage of the high ability of the general contractors and can fix the responsibility on it by using procurement like the design and build etc. Meanwhile, this strong point becomes the weakness of Japanese system, and it brings about the opacity of the organization and the fixation of the method of procurement. Moreover, cooperative relation established domestically prevents companies in construction industry from becoming independent from the domestic demand.

4.2 For Korea

The strong point of the management system of South Korea is as follows. The first is the supervisor which seeks profits on behalf of the client. It promotes projects maximizing the demand of the client on the strength of legal authority. The second is the leadership of the administration. By a variety of measures implemented by the administration, private companies are made to act unitedly.

But, such leadership of the administration becomes the weakness of management system of the South Korea production system. Various restrictions make it difficult for the private company to provide flexible service for the demand of the client because the production system of construction is improved at the initiative of the administration. The second weakness of management system of the South Korea production system is detailed regulations concerning the work of each subject. There is a possibility that the regulations make the contractor lose the consideration of important improvements. The third is the clear division of the scope of work of each party. Because the scope of work of each party is classified, the organization of the project becomes large and the locus of the responsibility might become obscure. Moreover, the effect of reflecting the technology of construction in design phase decreases.

5 Conclusions

The supervision system of the construction industry in Japan and South Korea and the feature of both countries are compared.

There are two types; government-initiated system based on law in South Korea and the Japanese system based on mutual-trust among each party. It cannot be judged so far which system is more efficient. However, it cannot be overlooked that an original system is developed according to the environment of the industry of the home country.

It seems that comparing the supervisor systems in each country promotes the change into the more effective production system.

Acknowledgments

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Quality management through construction process in China

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Abstract:

This paper introduces the result of a survey aimed at identifying the factors that affect the quality management system of construction process in China. This research was carried out to analyze the factors and to rank them according to their degree of importance. Two phases (design phase and construction phase) of construction's life cycle are identified. The perceptions of different participants are obtained by means of a questionnaire survey. Special focus is given to the impact that quality management system is the link among the owners, the designers, the supervisors and the contractors. It is anticipated that discussion of these factors will provide a basis for future strategies to promote the development of quality management in China, and also provide useful reference for the foreign countries to understand Chinese style of management.

Keywords: Quality management, Construction process, Factors, China

1. Introduction

During the last decade, the activities of quality assurance in most of the Chinese construction contractors have been limited to meet the technical specification of final products, with a strong dependency on the owner's inspection. In recent years this approach is hanging rapidly and several owners are now transferring the responsibility for quality assurance to the supervisors or the contractors [1].However, relatively speaking, the quality of construction is still at low level now. A number of quality management problems remain unsolved [2].

After reviewing the literature related to quality management of China, it is very clear that little research has been conducted in the area of quality management system (QMS) of Chinese construction industry internationally. Therefore, it is very difficult for foreign people to obtain relevant information on the QMS of Chinese construction industry. In order to provide readers with a better understanding on the QMS of Chinese construction industry, in this paper we presents the factors that affect the QMS and analyze these factors by making a global review of construction quality performance from the view of the owners, the designers, the supervisors and the contractors.

2. Practices of typical Chinese construction

In China a large number of projects are still contribute to the government funds, most of the owners and the contractors are government owned enterprises [3]. Moreover most of the construction projects are contracted using the traditional approach (fig.1), and other approaches like design-build or turnkey contracts are seldom used. The efficiency and effectiveness of Chinese construction projects are still low [4].

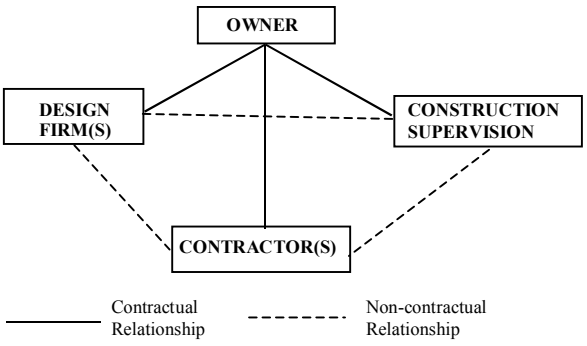

Fig.1 Forms of the traditional practice of Chinese construction project

Table 1
Factors affecting the quality management system of Chinese construction process

Factors affecting the quality management system of Chinese construction process		
Design phase	A-1	Lack of constructability in design documents
	A-2	Errors in design
	A-3	Lack of standard specification figures
	A-4	Un-share of design information
	A-5	Frequent design changes from owner
	A-6	Insufficient sense of responsibility of designers
	A-7	Shortage of supervisor's work
	A-8	Insufficient production-information
Construction phase	B-1	Frequent revision and change order by the owner
	B-2	Lack of cooperation from the owner
	B-3	Bad quality materials
	B-4	Delay in payment from owner
	B-5	Ineffective cooperation between contractors and designers
	B-6	Design changes
	B-7	Poor ability of supervisor
	B-8	Obscure function of supervision
	B-9	Poor construction plan of contractors
	B-10	Poor building technology of contractors
	B-11	Poor quality management systems
	B-12	Insufficient awareness of quality management in contractors
	B-13	Decrease in function of contractors
	B-14	Bad communication among contractors
	B-15	Bad communication among professionals concerned
	B-16	Ambiguous responsible scope of professional concerned
	B-17	Poor availability of equipment
	B-18	Bad quality of subcontract material

Owner

The practice of establishing construction projects in China involves the formation of a temporary Preparatory Office (PO), which represents the Ministry/Provincial/Municipal government in pursing projects. As the government wants to restrict information related to the financial situation and the progress of projects, the officers of the Government normally form PO. These people are responsible for the management and coordination of the project from beginning to end.

Design firm

The Chinese design firm (DF) basically plays the role similar to the architect/engineer (A/E) in the Western construction industry. However, a design firm is only responsible for the preparation of preliminary and detailed designs. Its duty terminates when the design works complete [5]. The design system in the Construction industry consists of various types of design firms based on their specializations, such as petrochemical, transportation and building, etc. This is unlike the practice in the Western construction industry in that the A/E performs various kinds of designs.

In international practice, the role of the supervision has traditionally played by the A/E as the engineer. This is because they have daily knowledge of the project in detail. However, the Chinese design firms only carry out the design works and are normally not responsible for supervision of the construction works.

Construction Supervision

The construction supervision (CS) is a legal requirement introduced in 1988 after the Provisional Construction Supervision Ordinance. The duties of CS are to supervise the works of a construction project as an independent third party. The aim is that the supervision should monitor various aspects of construction works, including the planning and control of project cost, timetable and quality [6]. Besides, the supervision responsibility will run through the project from beginning to end. Therefore, this hopefully complements the shortfall of the traditional Chinese construction practice, by bridging the gap between the design firms and the contractors.

Contractor

The Chinese contractor is the same as the contractor in the Western construction industry. The contractor is responsible for implementing the physical works of a construction project. The duty of the contractor includes the management of the construction site and its own resources, including the labor and construction plants. However, unlike the Western contractor, the contractor in China is not responsible for the procurement of materials, which is the duty of the PO for most of the projects. Moreover, the Chinese contractor usually does not carry out

detailed planning, such as method statement before the works carried out [7].

In addition, before the implementation of the Provisional Construction Supervision Ordinance in 1988, contractors were solely responsible for the construction quality under the supervision of PO. In the absence of an independent party to monitor the work, the quality of the works fluctuates.

3. Research Methods

3.1 Data Collection

The data for this research were collected using a questionnaire and supplementary interviews [8]. The investigation on the factors that affect the quality management system of construction process has attracted attention of many researchers. Based on the summary of the findings on this topic in literature [9] [10] [11], a questionnaire with 26 factors (table1) was devised. Owners' project managers (OP), design firms (DF), construction supervisions (CS) and main contractors (MC) were the main target respondents. By focusing on traditional procurement, ten completed projects were developed based on information obtained from the tender records of a major construction company in Beijing. Senior staff of owner organizations and construction firms was contacted, and through them key project participants of each projects were identified. Questionnaires were distributed to individual project participants and those who agreed to dispatch questionnaires to their project team members.

40 questionnaires in total were delivered; finally, 32 questionnaires were received (Table2).

Table 2
Rates of return

Part	Number of questionnaires mailed	Number of responses received	Rate of return %
OP	10	5	50
DF	10	8	80
CS	10	9	90
MC	10	10	100
Total	40	32	80

3.2 Measures

Respondents were requested to rate all the factors affected construction process quality management according to a five-point liker scale where 1 represented the lowest level of influence and 5 the highest. Respondents were also requested to provide information about quality management performance of the project in which they were involved.

4. Findings and Analysis

Table3, Table4 presents the ranking of the nominated factors based on the value of their means.

The following discussion will emphasize 8 factors (3 factors in design phase, 5 factors in construction phase) with the rank according to the mean value.

4.1 Factors affecting quality management system in the design phase

The ranking in Table 3 reveals that the ideas change with positions of each part. *Errors in design* were found to be the most important factor by the owners' project managers. Both the supervisions and the contractors regard *Insufficient production-information, Lack of constructability in design documents* as the first and second factor.

Insufficient production-information

According to the traditional approach, the demerit of this procurement is that the contractors can not participate in the planning and design works, which results in the loss of feedback on construction for the designers. Consequently, coordination problems between the design team and construction team will be increased dramatically. The competence will greatly impact the quality of design documents and services other than design.

Through the division of construction labor and the rapid change of construction technology, problems about the shortage of production-information and the lack for constructability in design documents is becoming more and more important.

Un-share in design information

Under the socialist system, the Chinese design firms were divided into the field of structural design and equipment design. In a project, special design teams are made up: basic design, mainframe construction design, drain design, and electric equipment design, etc [12]. Each team is responsible for the work of its own, but does not pay much attention to the entire design quality, much less the transmission of design information and communication between the teams [13]. Therefore, the mismatch between separate works is caused. A great deal of design changes are often urged in the construction stage. This factor is thought to be one of the main reasons to cause design errors.

Insufficient sense of responsibility of designers

As in other Chinese industrial enterprises, most of the design firms are state enterprises. These design firms do not have reasonable balance of national profit, corporate profit, and individual profit for a long term, and there is no clear rewards and punishments system [14]. There prevents employees from improving their sense of responsibility. In addition, as mentioned above, each design team assumes the responsibility of itself only. We think the

Table 3
Ranking of the factors affecting quality management system in the design phase

Party	Rank	Factor No.	Factors	Lowest ← 1	2	3	4	5 → Highest	Means
OP	1	A-2	Errors in design	0	0	2	1	2	4.0
	2	A-6	Insufficient sense of responsibility of designers	1	0	1	1	2	3.6
	3	A-8	Insufficient production-information	0	1	2	0	2	3.6
DF	1	A-4	Un-share of design information	0	0	2	2	4	4.3
	2	A-8	Insufficient production-information	0	1	3	2	2	3.6
	3	A-6	Insufficient sense of responsibility of designers	2	2	1	1	2	2.9
CS	1	A-8	Insufficient production-information	0	1	2	2	5	4.3
	2	A-1	Lack of constructability in design documents	0	1	2	2	4	4.0
	3	A-6	Insufficient sense of responsibility of designers	0	1	2	3	3	3.7
MC	1	A-8	Insufficient production-information	0	0	0	2	8	4.8
	2	A-1	Lack of constructability in design documents	0	0	1	2	7	4.6
	3	A-6	Insufficient sense of responsibility of designers	0	0	2	3	5	4.3

Table 4
Ranking of the factors affecting quality management system in the construction phase

Party	Rank	Factor No.	Factors	Lowest ← 1	2	3	4	5 → Highest	Means
OP	1	B-12	Insufficient awareness of quality management in contractors	0	0	0	1	4	4.8
	2	B-9	Poor construction plan of contractors	0	0	1	0	4	4.6
	3	B-6	Design changes	0	0	0	2	3	4.6
	4	B-5	Ineffective cooperation between contractors and designers	0	1	1	1	3	4.4
	5	B-14	Bad communication among contractors	0	0	1	0	3	4.0
DF	1	B-9	Poor construction plan of contractors	0	2	2	2	4	4.3
	2	B-12	Insufficient awareness of quality management in contractors	0	1	1	2	3	3.8
	3	B-11	Poor quality management systems	0	1	3	2	2	3.6
	4	B-14	Bad communication among contractors	0	2	3	2	2	3.6
	5	B-15	Bad communication among professionals concerned	0	0	2	1	3	3.6
CS	1	B-14	Bad communication among contractors	0	0	0	2	7	4.8
	2	B-9	Poor construction plan of contractors	0	0	1	1	7	4.7
	3	B-6	Design changes	0	0	2	1	6	4.4
	4	B-12	Insufficient awareness of quality management in contractors	0	1	1	1	6	4.3
	5	B-15	Bad communication among professionals concerned	0	0	2	2	4	4.0
MC	1	B-6	Design changes	0	0	0	2	8	4.8
	2	B-9	Poor construction plan of contractors	0	0	1	2	7	4.8
	3	B-12	Insufficient awareness of quality management in contractors	0	0	1	1	8	4.7
	4	B-5	Ineffective cooperation between contractors and designers	0	0	2	2	6	4.4
	5	B-8	Obscure function of supervision	0	0	2	3	5	4.3

quality consciousness of Chinese designer is lower than that of Western designers.

4.2 Factors affecting quality management system in the construction phase

Table 4 shows *Insufficient awareness of quality management in contractors, Poor construction plan of contractors , Bad communication between contractors and Design changes* are given to the most important factors respectively by OP,DF,CS and MC. Though it is presumable that each participate in project has the tendency to attribute the cause of the problems to other parties, the weakness of construction management can be said to be the main problem in construction phase. Excluding DF all the other parties regarded *lack of a contractor's construction plan* as the second factor that affects the quality management system in the construction phase.

Insufficient awareness of quality management in contractors

Apart from the reasons discussed above, there might be two special reasons to cause the Chinese contractor's poor quality consciousness.

- Under the socialist system, all building products are owned to state. The contractors cannot clearly recognize the correspondence between the quality and enterprise earnings, they cannot connect the confidence of quality management with a long-term profit of enterprise.
- Employer's incompetence is the other reason for the cause of low quality. In general, the technical competence of Chinese contractors at technician level is high, as they are normally highly educated and have sufficient technical knowledge in the trade. However, most of the people at worker level are unskilled and a lot of them are not all the year round construction

workers. As a result, the quality of works is often not guaranteed [15].

Poor construction plan of contractors

In China, construction process plan is not made at the site but in the technological section at the enterprise. Technological idea and construction measures are given priority in the content of construction plan; consequently, the plan lacks consideration for the design intention, change in the plan or coordination between the construction works [16]. Moreover, the working drawing that made by the designers is used directly to the site even though they stay in the expression of the design intention only. Therefore, it can be guessed that the level of construction plan quality based on such working drawings is not high.

Bad communication among contractors

The problem of *Bad communication among contractors* was thought to be caused by the insufficient plan management of main contractors and the lack of subcontractors' cooperative consciousness. Unlike the contractors in other countries, Chinese contractors are not required to coordinate with others [5]. This will limit their ability to take account of the needs and expectation of other contractors.

Design changes

Design changes were considered to be the most important factor by the contractors. It may result in changes in design and spending more time on rework. Consequently the contractors might exceed the timetable or budget to complete the project if additional time and cost are not allowed. In such case, the contractors cannot give warrantee of the construction quality.

In China, the problems of design changes were thought to be caused by the contractor's technology and the insufficient consideration for constructability of designers. In addition, as described in *4.1*, the gap of information between design and construction, and poor quality of design documents are the other main reasons to cause design changes.

Poor quality management systems

TQC (Total Quality Control) and ISO (International Organization for Standardization) 9000 are used as the quality control system by the Chinese construction enterprises normally. Recently, like other sectors in the Chinese industry, the organization of construction enterprise is also reformed. Inspection supervisor or quality guidance from enterprise's headquarters has decreased than before [5]; the quality control enactments such as revision, execution, supervision and inspection, etc. are all taken charge by the site. However, not all the sites have the ability to manage independently. Basic education of quality control, quality control activities and the feedback of quality information are not always ensured. Moreover, as mentioned above, it is difficult to set up quality management system in the site because of the bad consciousness of quality of the contractors.

The other factors

- *Ineffective cooperation between contractors and designers*

It is widely agreed in the construction process that the designers need to visit the sites and attend site meetings frequently to familiarize themselves with the progress and problems in construction. However, as described above, in China, the designers seldom get involved in during the construction phase. Normally they only go to the site when there is a big problem or need to attend the joint inspection [5]. This is quite different from the practice in UK, or US where the original designers are often employed as the owner's representatives to supervise the construction works. The ineffective cooperation between the Chinese contractors and the designers will greatly impact the quality management of the total construction process.

- *Obscure function of supervision*

Obscure function of supervision was considered as the fifth factor by contractors. The factor can be caught by the limit of CS' management and the problems of CS qualification system. Although CS is adopted to bridge the gap between design teams and construction teams, in fact the performance cannot be fine. Besides, the CS only take on the duty of construction site supervision, and seldom participate in the cost and progress management. This has restricted the professional development of CS [17]. As a result, this also restrained the improvement of construction quality management in China. This paper, however, will not discuss about CS further. Readers may refer to other sources for more detailed information [18].

5. Conclusions

The quality management problems in Chinese construction industry are both complex and deep rooted, influenced by many factors operating on procurement system, designers, contractors, supervision, and construction industry etc. From the above analysis, we have gained the following conclusions: the most common factors affecting the quality management of construction process have been identified. Specifically, *Un-share of design*

information, Insufficient production-information, Lack of constructability in design documents, contractor's Poor consciousness of quality, Lack of contractor's construction plan **,** *Bad communication among contractors and Design changes* are the important factors that affect the quality management system of construction process .

Based on the results of the surveys, some suggestions for better quality control are pointed out as follows:

- Make closer coordination between designers and contractors during the design phase. This will enhance the constructability of design; decreasing design change, introducing innovation and value engineering aspects in design. Construction companies are advised to adopt design-build, turnkey or other procurements in order to take more attention to quality management in the early stages of the design phase.
- At the corporate level, teamwork or partnership appears to be of importance to improve quality. Project participants should recognize that cooperation as well as technology represents the key elements of quality in whole project.

  To solve the problem of weak link among contractors, the main contractors should actively participate in the implementation of quality-enhancing measures and commitment. All the parties concerned with construction should get involved in the process of improving quality on a continuous basis.
- Construction plan was found to be the most important task (ranked second in the construction phase by OP, CS, and MC); especially if work is subcontracted to a variety of subcontractors. From the subcontractors' point of view, lack of information and overlapping activities, which are common on the site, may result in rework and low quality performance. Improved communication and shared information may increase the effectiveness of the plan made by the contractor. According to Stub [19], a distributed database for project control may improve the quality of construction plan.
- It is important to organize training courses for people at work level. Since most of the workers in the Chinese construction industry are undereducated, training for the workers by trade will enable them to have a thorough understanding for the quality requirements. Hence the quality of the construction project would also be improved.
- Despite the management and technology constraints, there are still many points to be improved within individual design firms and contractors. Efforts should be made to further enhance the designers' and the contractors' quality awareness and consciousness.

Acknowledgements

The authors would like to express their sincere gratitude to consultants and contractors who kindly participated in the survey and interviews. The authors are also very grateful to anonymous reviewers for their valuable comments to this paper.

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3-D REAL-TIME ACCURACY CONTROL OF AUTOMATED ROAD CONSTRUCTION MACHINES

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Abstract: This research studied the possibilities for utilizing different *a priori* types of measuring algorithms in order to improve accuracy and reliability of automated machine control in road construction. Generally in measurement science different *a priori* types of algorithms have widely been used to estimate beforehand the propagation of randomly appearing errors. While the exact mathematical solutions for derivative measurement quantities, as well as the random errors of fundamental quantities are known, the random errors of derivative quantities can always be evaluated using stochastic mathematics. In principle, this type of stochastic model can give us the magnitude of the highest attainable accuracy in practical measurement situations. In our research, new stochastic models to determine the random errors of robot tachymeter in kinematic measurement situations were developed and introduced. The tested tachymeter was TRIMBLE ATS. The needed random errors for the test solution were determined based on the technical specifications obtained from Trimble. In addition, two different kinematic calibrations for the use of robot tachymeters for road construction automation were developed and executed.

Keywords: automation in construction, accuracy control, stochastic models, intelligence in automation

1. INTRODUCTION

In practical road construction the direct use of automated machine control systems for construction work sets great demands for maintaining adequate control accuracy of the utilized technologies. The economic consequences of deviations can be very significant. Until today the possibilities of these *a priori* types of algorithms have not been applied in the domain of road construction automation. Also, manufacturers of tachymeters have not presented the exact positioning accuracy of their products. For example, Trimble presents that the accuracy of Trimble ATS 600 in dynamic operation is as follows: maximum acceleration of target (radial acceleration) 10 grad/s and 29 deg/s^2, maximum velocity of target (radial speed) 25 grad/s or 23 deg/s, and axial speed 6 m/s. In addition, Trimble presents that accuracy at constant speed of 1 m/s at 300m (standard deviation) is ± 2 mm + 14 ppm in horizontal and vertical distances. The question is: What kind of accuracy can we obtain in other situations?

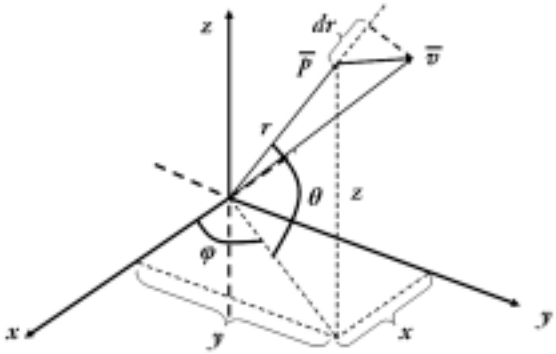

Figure 1. The dynamic situation of 3-D positioning measurement by a robot tachymeter in an arbitrary machine control application.

2. STOCHASTIC MODELLING AND TESTING

New stochastic models to determine the random errors of a robot tachymeter in a kinematic measurement situation were developed and introduced. The tested tachymeter was Trimble ATS. The needed random errors for the test solution were first determined based on the

technical specifications obtained from Timble. In addition, three different kinematic calibrations for the use of robot tachymeters for road construction automation were developed and executed in conjunction with Helsinki University of Technology and the Finnish importer Geotrim Oy.

The required functional equations for cartesian *x*, *y,* and *z* coordinates are

$$\begin{cases} x = r\cos\theta\cos\varphi \\ y = r\cos\theta\sin\varphi \\ z = r\sin\theta \end{cases} \quad (1)$$

where *r,* θ, and φ are the basic spherical coordinate observations of a tachymeter. To evaluate the uncertainty of the measurements, the propagation of random errors must be cleared. Assuming that normally distributed random variables are considered, the uncertainty of the independent spherical coordinates at a given point can be illustrated by the covariance matrix

$$C_p = \begin{bmatrix} m_r{}^2 & 0 & 0 \\ 0 & m_\theta{}^2 & 0 \\ 0 & 0 & m_\varphi{}^2 \end{bmatrix} \quad (2)$$

where m_{r^2}, m_{θ^2}, and m_{φ^2} are the variances of spherical coordinates. The covariance matrix of cartesian coordinates is

$$C_c = J_{cp} C_p J_{cp}{}^t \quad (3)$$

where

$$C_c = \begin{bmatrix} m_x{}^2 & m_{xy} & m_{xz} \\ m_{xy} & m_y{}^2 & m_{yz} \\ m_{xz} & m_{yz} & m_z{}^2 \end{bmatrix} \quad (4)$$

and

$$J_{cp} = \begin{bmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} & \frac{\partial x}{\partial \varphi} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} & \frac{\partial y}{\partial \varphi} \\ \frac{\partial z}{\partial r} & \frac{\partial z}{\partial \theta} & \frac{\partial z}{\partial \varphi} \end{bmatrix} \quad (5)$$

The uncertainty of static measurement C_{static} is mathematically fully determined since the uncertainties m_r, m_θ and m_φ are now known, Eq. (2). The needed variances and covariances can be solved from Eq. (1) and Eq. (3) and are

$$\begin{cases} m_{x^2} = (\cos\theta\cos\varphi)^2 \cdot m_r{}^2 + (-r\sin\theta\cos\varphi)^2 \cdot m_\theta{}^2 + \\ (-r\cos\theta\sin\varphi)^2 \cdot m_\varphi{}^2 \\ m_{y^2} = (\cos\theta\sin\varphi)^2 \cdot m_r{}^2 + (-r\sin\theta\sin\varphi)^2 \cdot m_\theta{}^2 + \\ (r\cos\theta\cos\varphi)^2 \cdot m_\varphi{}^2 \\ m_z{}^2 = (\sin\theta)^2 \cdot m_r{}^2 + (r\cos\theta)^2 \cdot m_\theta{}^2 \\ m_{xy} = \frac{1}{2}\sin 2\varphi \cdot (\cos^2\theta \cdot m_r{}^2 + r^2\sin^2\theta \cdot m_\theta{}^2 \\ - r^2 \cdot \cos^2\theta \cdot m_\varphi{}^2) \\ m_{xz} = \frac{1}{2}\sin 2\theta \cdot (\cos\varphi \cdot m_r{}^2 - r^2 \cdot \cos\varphi \cdot m_\theta{}^2) \\ m_{yz} = \sin^2\theta \cdot m_r{}^2 + r^2 \cdot \cos^2\theta \cdot m_\theta{}^2 \end{cases} \quad (5)$$

In a dynamic measurement situation we should know the additional uncertainties of spherical observations *r, θ,* and *φ*. When simplified, based on the Fig. 1, we can assume that additional uncertainties arise from the velocities and accelerations of spherical coordinates. With Eq. (3) we can deduce the uncertainties of the cartesian coordinates in the case of static measurement. This is based on the known uncertainties $m_r{}^2$, $m_\theta{}^2$, and $m_\varphi{}^2$ of the fundamental quantities *r*, *θ,* and *φ*. The uncertainty of a kinematic positioning situation can be estimated if we know the additional uncertainty caused for velocities and accelerations of v_r, v_θ, v_φ and a_r, a_θ and a_φ. Thus, the task is to calibrate the dependencies between the spherical velocities and accelerations, and the additional uncertainties.

One special case in a dynamic positioning situation is the shaking of a prism. Based on the practical observations in the case of a road grader, we can estimate the additional

uncertainty being generated by shaking with the equation

$$C_{shaking} = \begin{bmatrix} m_x^2 & 0 & 0 \\ 0 & m_y^2 & 0 \\ 0 & 0 & m_z^2 \end{bmatrix} \quad (6)$$

where we can further assume $m_x^2 = m_y^2$ since the shaking in different horizontal directions is identical.

An Excel sheet application was developed to test and utilize these models. The first calculations were executed by using own estimates for the additional uncertainties caused by velocities, accelerations, and shaking. For a more accurate and usable utilization two different types of dynamic calibration tests were executed using Trimble tachymeters, Figs. 2-4. A third calibration with Leica tachymeters has also been planned.

Figure 2. Calibration test using three Trimble tachymeters at the gym hall of Oulu International school.

Figure 3. Calibration test using three Trimble tachymeters at the Kestilä Airfield

3. TEST RESULTS

The first test results of the models are presented in the Figures 4-6. In these example calculations r=200 m, φ=30°, θ=25°, v_r=2,4 m/s, v_φ=0,006 °/s, v_θ=0,001 °/s, m_r=5.0 mm, m_φ=0,004 °/s, m_θ=0,004 °/s, $m_{xy\text{-}shaking}$=100 mm, $m_{z\text{-}shaking}$=5 mm, m_{vr}=2,4 mm, $m_{v\varphi}$=0,0000024°, $m_{v\theta}$=0,0000004° and m_{ar}=2,4 mm, $m_{a\varphi}$=0,003°, $m_{a\theta}$=0,003°. These values are evaluated only for this calculation test.

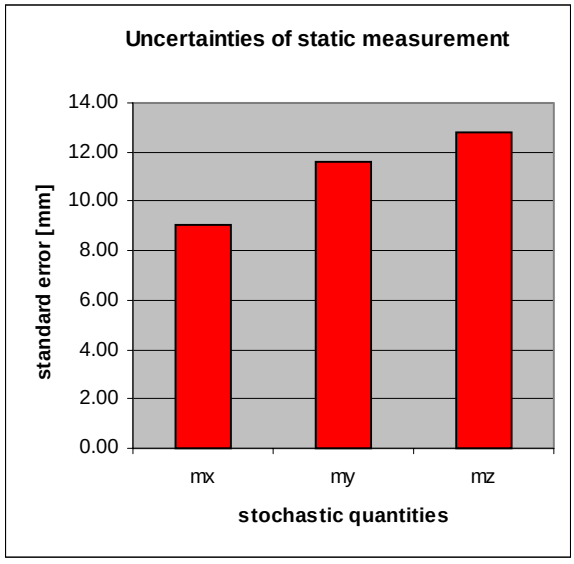

Figure 4. Random errors of static measurement in the test situation.

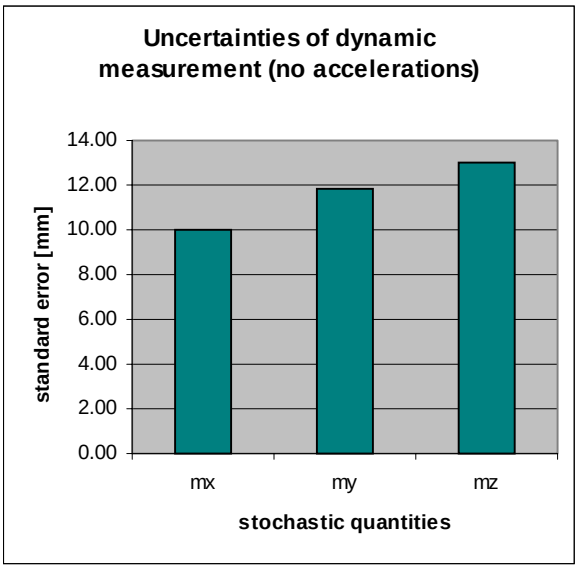

Figure 5. Random errors of dynamic measurement (static + shaking + velocities) in the test situation.

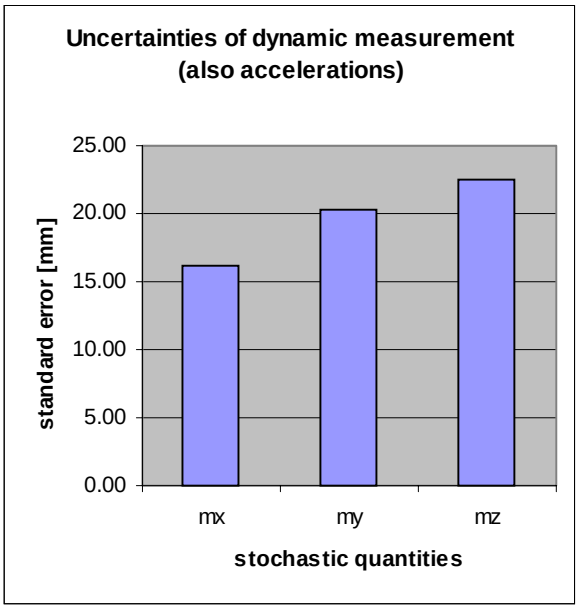

Figure 6. Random errors of dynamic measurement (static + shaking + velocities + accelerations) in the test situation.

4. CONCLUSION

Based on the test results, the developed stochastic models can be used to estimate in real-time the 3-D positioning accuracy of mobile work machines. The mechanisms of different random errors are complicated. The presented model is a simplified mathematical solution with which it could be possible to real-time control the behavior of random errors. In principle, it is possible to connect these models directly to a part of the automated control system of machines. It is also possible to extend these models to control the accuracy of the whole blade control system. Thus, the final accuracy of moving blades could be controlled in real-time. This technique means that more intelligence, accuracy, and reliability can be achieved in the automated control of construction. In the future, this type of intelligence could be first implemented, for example, into the automated control of a road grader. The calibration of additional uncertainties requires a series of careful tests to be generally utilized. The first calibrations have been executed in Finland during Spring-Summer 2004.

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TOWARDS MODEL BASED AUTOMATION - DIFFERENT TYPES OF 3-D MACHINE CONTROL MODELS FOR THE AUTOMATIC CONTROL OF ROAD CONSTRUCTION MACHINERY

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Abstract: In this paper the type of CAD model-based automation is studied for the domain of infra construction tasks. The needs for machine control models vary from machine to machine. This paper describes as examples the machine control models needed for *road graders*, *asphalt pavers*, *excavators*, *milling machines* and *steamrollers* – the most typical work machines used in road construction activities. The paper also describes how these machine control models can be conducted from the product models. The usability of the control models was tested by on-site experiments using applicable automation systems. Furthermore, the necessary feedback from automated construction to the product model was also considered. This was done by measuring the quality and accuracy of the constructed work. In all and as a final conclusion, these tests represent and model the total process of road construction automation: what are the parts and how they work together.

Keywords: automation in road construction, 3-D CAD, machine control models

1. INTRODUCTION

Automation means self-acting or self-sustaining operation. The automated operation of machines can generally be divided into three different types: *teach-in*, *model-based* or *fully autonomous* operation. Teach-in is the simplest one. The machine is taught the necessary operation by driving a motion series using manual control. All of the motions of the used joints and regulating units are recorded at the deeded time intervals. It is also possible to repair a part of the whole taught motion. Finally, the machine can automatically repeat the driving it has been taught. Secondly, it is possible to generate a special machine control model on account of its earlier planned product model. This is a more advanced automation type. The availability of the product model is necessary. To utilize model to machine control we must calculate real-time and coordinate the needed motions for every part, joint and unit of the machine in question. For the most versatile applications all the kinematics must also be solved. Thirdly, it is possible to develop fully automated systems. The robot is equipped with the required number of sensors and it has the ability to operate in real-time and automatically generates its control model. All of the motions of different parts are calculated in real-time and through total kinematics and its inverse solutions.

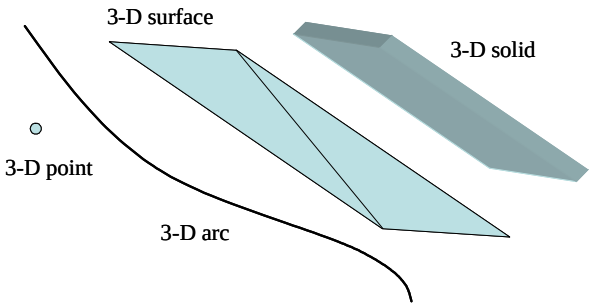

Figure 1. Basic 3-D geometric elements available for machine control applications.

2. MODEL BASED ROAD CONSTRUCTION

2.1 Modeling process

Preparing initial data for road geometry design starts with terrain modeling and ground surveying processes. Measured data is classified and translated for the utilization road geometry planning process (fig. 2).

The general road geometry design method is composed of the next basic stages: horizontal geometry alignment, vertical geometry and cross section design. The road design process generates most of the required information for machine control. In particular, machine control (MC) models for road superstructure construction can be designed based on basic road geometry. Again the 3-D models produced in road design the CAD applications, cannot be used directly for machine control systems. Road geometry as 3-D arcs or lines are then transferred to machine control CAD tools. Finally, MC-models as 3-D surface models, staking out –lines, are produced to an applicable format for different MC control systems. On-site operation MC-models are used in MC-systems as a reference to guide the operator and directly to control the machine blade.

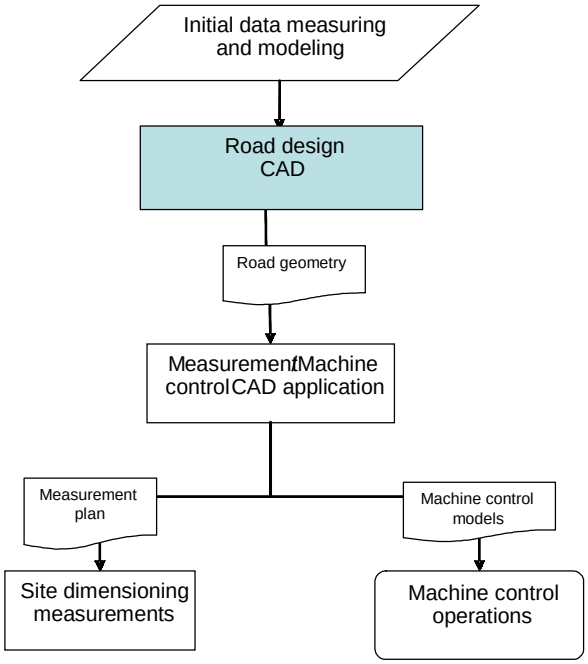

Figure 2. Information process from initial data measurements to site operations.

2.2 Development needs of road design CAD applications

According to a survey carried out among Finnish road design consultants in the spring of 2004, the main drawbacks of road design CAD software in structural modeling are related to the tools used for adapting the road cross sections and structures to the terrain. Areas where improvements are called for include the development of the modeling and cross-sectional tools for structural geometry in such a way that the changes made to the cross section during design are automatically updated to the geometry of the lines and models and vice versa. Additionally, it should be possible to design the road alignment, leveling and cross section both visually and by using parameters. At the same time, the efficiency of the design system should be improved to allow quick comparison of different alignment and leveling options, inclusive of the calculation of quantities and relative costs. A shared goal for all road design CAD software developers is the adoption of standardized data transmission formats for input data entry and design data transfer to other systems. Another future objective is to put in a place a shared logic processing model for the entry and reprocessing of design data.

3. TEST RESULTS

The production of MC models is based on three items: firstly part of the road structure under construction work, second, the chosen working method and third, the machine type and the MC system involved. The MC modeling process is different depending on whether the focus is a new road or the renovation of an existing one.

For pavements and other super road structure layers, a typical MC model is 3-D surface model and 2D-control lines. This model only contains geometrical information about a road structure's elevation, the cross-fall and bending lines (convex or concave lines). The MC system can use the surface model for controlling elevation and cross-fall of a certain machine's blade. This kind of MC model can be used for controlling the motor grader, the paver and the milling machine (Fig.4). The same kind of MC model can also be utilized for an excavator when carrying out road sub-grade cutting and filling works. On the other hand consolidation work or the piling of road base requires different kinds of MC model (Figs.6 and 10).

The production phases of MC modeling for the road grader is presented in figure 3. One important task in the modeling process is to

connect different 3-D bending lines to form a continuous geometry. This also allows for the to creation of a continuous MC model, which has been proven to be profitable at on-site operations. For example, freeway lanes and the involved exits should integrate to the same MC model. Test results at freeway construction sites demonstrate that the extensive model minimizes the amount of possible breaks and provides better geometrical accuracy. Generally, a model-controlled grader is 50-100% more efficient than a traditional one. MC models produced for a grader can also be utilized for other machines, as a gravel spreader or a paver. The maximum benefit in model-based road construction is achieved when a group of machines are performing the same task and using the same MC models (Table 1).

The MC modeling process for the asphalt paver is basically the same as for the motor grader. The paver moves more slowly than the grader, but the required accuracy is more critical. The necessary level of automation in the paver is not as high as with a grader. The operator of the screeding blade still has enough time to control the blade himself, but at the same time he can take advantage of the MC system. In paving work, the invoicing basis is usually kilograms per square meter. In practice this concludes to contractor to make constant asphalt layer thickness. Despite the fact that MC models cannot always be used for controlling the thickness of the asphalt layer, cross slope and driving line guidance are valuable aspects to exploit. If concrete structures, such as bridges, are already modeled, these models can be put to good use in the paving process (fig. 9)

The geometrical MC modeling process for milling machine control depends on the level of road renovation work and the work method to be used. If renovation work concerns for example highway repavement the modeling process is basically the same as for the finisher. Before the MC modeling process is possible, the existing road geometry should firstly be measured and then the new geometry can be modeled. After that, road renovation design can be carried out in the 3-D CAD applications.

The milling machine is also used for cutting the old pavement and mixing it with the other road super structures. In Finland this is the common repair method for smaller roads. When the initial 3-D data is not available, an adequate MC model includes 2D-roadline and the amount of binder as well as the thickness of the layer to be stabilized (Fig. 5).

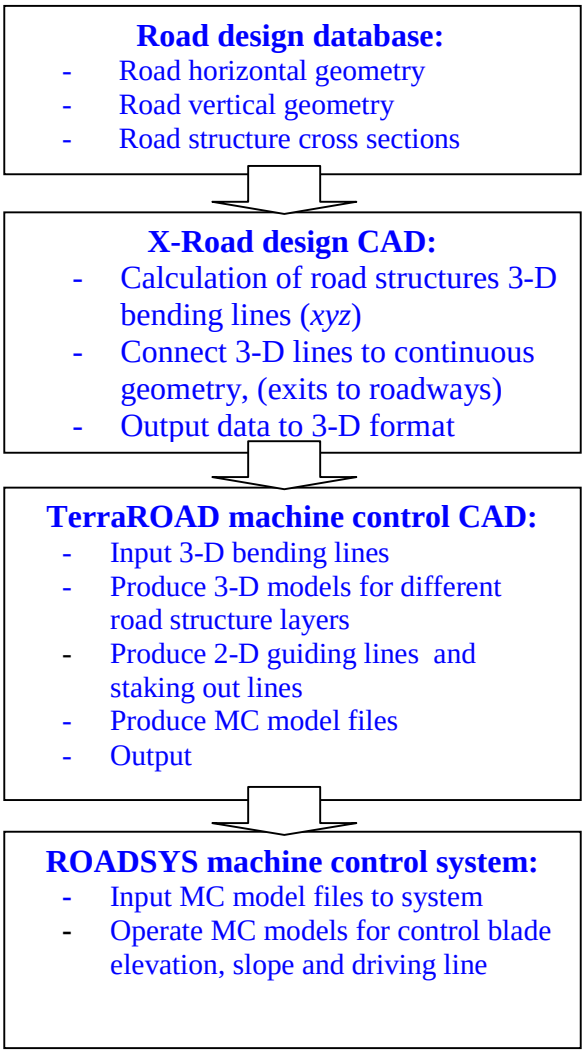

Figure 3. The phases and tools used to design MC models from the product models.

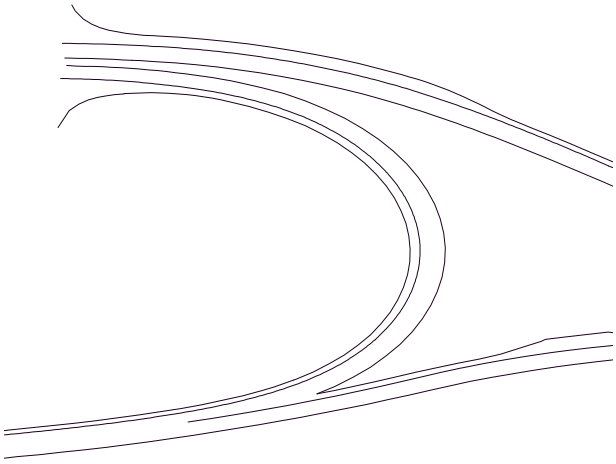

Figure 4. 3-D bending lines of the road structure layers are used as initial data for the MC model.

When an excavator is used for example in open cut or sub-base cutting works (fig. 7), the 3-D surface model of the structure is adequate initial information in order to produce the MC model. This model contains the required information about the structure's elevation and cross-fall. The excavator is typically used to finish the inner and outer slopes of the road ditch. In this case, in addition to the 3-D surface model, 3-D shoulder and ditch bottom lines are also needed for MC modeling.

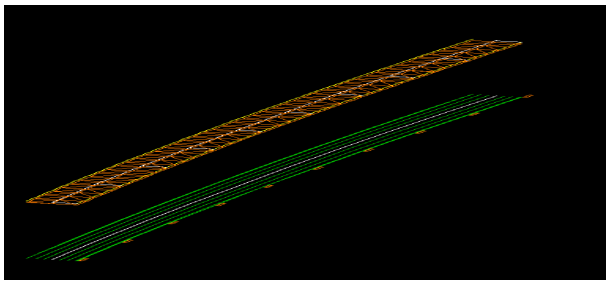

Figure 5. Type of machine control model for a road grader, mass spreader and asphalt paver: 3-D edge lines (lower) and height level (upper) is enough for most practical cases.

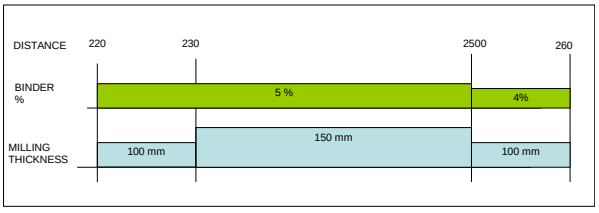

Figure 6. MC model required for milling machine. The necessary control items are the amount of binder as well as the thickness of layer to be stabilized.

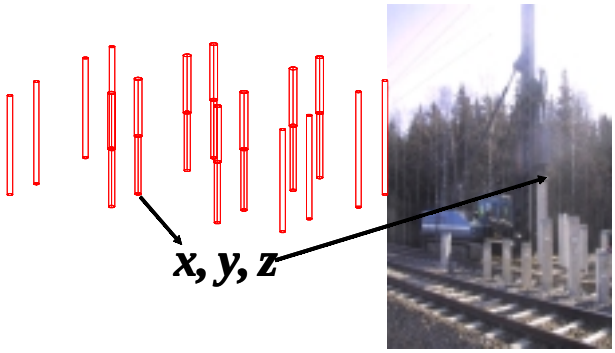

Figure 7. An example of machine control models:3-D locations of points for the piling machine.

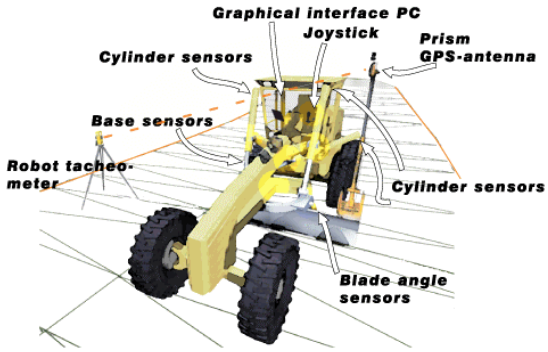

Figure 8. CAD model connected to the entirety of an automated control system of road grader.

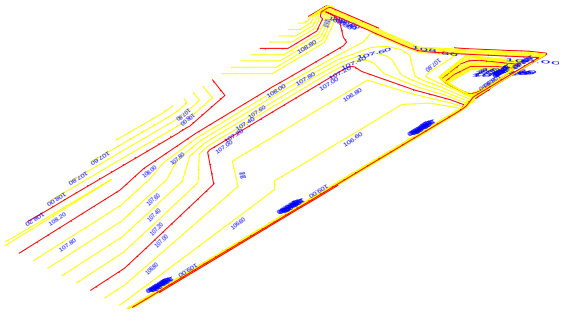

Figure 9. An example of an excavation machine control model – 3-D model of a dump base.

Figure 10. A model of a bridge superstructure can be used to control the paving process.

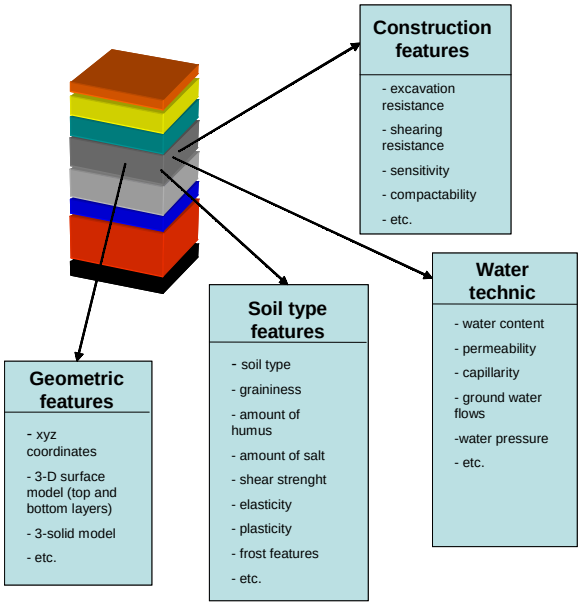

Figure 11. A sketch of advanced machine control models needed for stabilizing machines.

4. CONCLUSION

As far as road superstructures are concerned, solutions for producing workable control models for graders, pavers and excavators are already provided by existing software tools. Various machines used for carrying out the same work operations and implementing the same structures in road reconstruction can, to a great extent, make use of the same MC models based on 3D surfaces and lines.

Different types of CAD models are needed for the control of sub-base cementing work machines. The level of automation means that the required type and amount of information varies from machine to machine from very simple 3-D point models to complicated 3-D solid models integrated with numerous attributes.

A chief objective for model-based road construction is to develop site operations by improving productivity and the quality of structures. In principle, the existing models are easy to produce, provided that 3D plans are available for the site. With up-to-date tools, producing the models takes little time without affecting the economy of deploying MC systems.

The existing MC models are geometry models that include a mathematical surface plane as well as the horizontal geometrical lines of the bending lines. While they are accurate and reliable enough for controlling work machines, they are still unsuitable for more extensive automatic control of the site processes. Use of the existing models for road construction contributes to a better management of the site but it is safe to say that greater benefits can be expected when other information that supports and directs site activities, such as timetables, materials data or problem response procedures, can be incorporated in the models in addition to geometry data. Additional research is required to make it possible to use MC models beyond individual work machines for the purpose of controlling site activities more widely.

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Table 1. Work machine grouping road structure construction to be automated and estimation of automation needs and benefit potentials.

Working task	Machine	Automated functions	Benefit potentials
Loading	**Wheel loader**	**Load scale, wireless data transfer**	**Material savings**
Transport and unloading	**Kuorma-auto**	**Documentation of loading data**	**Material savings, Work method efficiency**
Gravel spreading	**Gravel spreader**	**3-D control system : layer thickness, cross slope, driving direction**	**Material savings, quality, surveying costs –50%**
Milling and stabilization	**Milling machine**	**2D/3D control system: milling thickness, binder quantity, cross slope, driving direction, documentation**	**Material savings, - 2%, surveying costs - 50%, quality benefits**
Finishing	**Motor Grader**	**3-D blade control system: blade control in all directions**	**Capacity + 50-100%, material savings 3%, surveying costs 50 %, documentation**
Paving	**Asphalt paver**	**3D-control system**:	**Material savings 2%, surveying costs 50%, documentation**
Compaction		**2-D control system: documentation of density, driving control**	**Quality of road structure**

APPLICATION OF 3D-MC FOR ROAD CONSTRUCTION MACHINE

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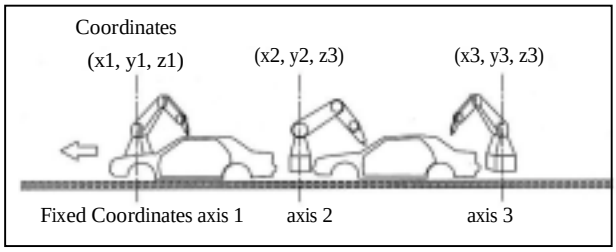
Abstract : Rapid development of computer or communication technology brought the IT, Information Technology, to the road construction field also. IT may include possibility for rationalization of job site work. Among them, new technology 3D-MC, 3 Dimensional Machine Control system, can unify following data, field design, survey, and machine control. Therefore 3D-MC is able to control the construction machine direct with field design data based on CAD. By using 3D-MC will bring cost down to job site.
Kajima Road had applied 3D-MC since 2000, and adapted to bulldozer, asphalt paver, and motor grader. By actual work, we had confirmed the efficiency and the accuracy of the 3D-MC installed construction machines. So we present about 3D-MC installed motor grader.

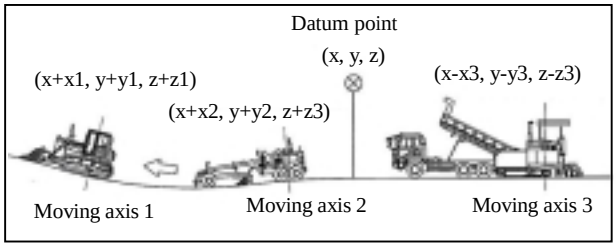
Keyword : Information Technology, 3 Dimensional-Machine Control system, Auto tracking, Total Station, System flow, High Accuracy

1 COPMARE OF JOB-SITE WORK AND FACTORY WORK

As we talk about rationalization of construction work at job site, it is always compared with factory work, and pointed out irrationality of construction work. When the industrial factory robots work, they are controlled with exact position information between tools of robots and processed object. About the job site, construction work is based on the information of coordinates that had been surveyed. As an operator controls construction machine, he uses such surveyed information indirect.



(a) Factory work: The coordinate axis is fixed, easy to sense the coordinates



(b) Job site work: The coordinate axes are always moving, difficult to sense the coordinates

Figure 1. Difference of sensing coordinates axis between factory work and construction work

Information technology, supported by computer, realized survey instruments gained automatic measu-rement function. Such instruments are used not only surveying but also machine control, which contribute rationalization of construction work.
These instruments can transfer coordinates data to construction machine, the transferred data controls actuators of the construction machine directly, this process is very similar to the industrial factory robots. We would like to say automation is no longer only factory robots.

1-1. Manual operation of usual machine control

About job site work, The thing should be do first is setting survey stakes at even interval they are used as reference points while construction work. Machine operator refers these stakes with his eyes as he operate the machine but he need to correct declination of stakes and actual working face, because stakes were set higher than actual working face.
Therefore result of working face or accuracy includes difference in the cause of level of operator's ability.

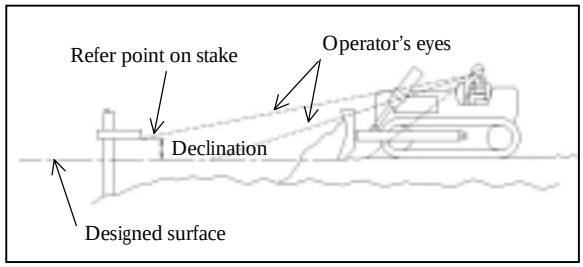


Figure 2. Manual operation, operator refers reference the stakes

1-2. Actual example of machine automation

There is an actual example system of machine automation, is setting surveyed string wires for machine control along the working lane. The sensor, installed on machine, which traces these wires to copy designed shape. This system can reduce the difference of operator's ability, and expect improvement of the accuracy. Especially, this system is used for paving machine. But setting the wire needs a lot of survey work and a large amount of labor.

Photo 1. Stakes for machine control set on slope

1-3. A sphere of construction machine automation

Process condition of construction work is not stayed constant, so almost part of machine work rely on human operation. Therefore the machine full-automation is much more difficult than industrial machine control. Accordingly, we do not need fully automated system, just need the system which supports operator to gain high quality unaffected by difference of operator's ability.

3D-MC can control the construction machine directly with design data, does not need to put stake, can save manpower to put stake and reduce operator load, and can increase safety in the job site, because 3D-MC does not require labors who do measuring around the construction machine. And in the case of using 3D-MC for survey work, a foreman of job site can unify data management.

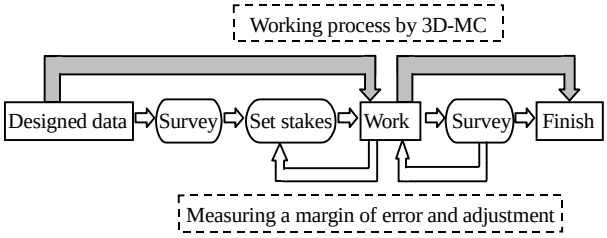


Figure 3. Comparing working process 3D-MC and existing way

2. 3D-MC BASED ON SURVEY INSTRUMENT FUNCTION

In case, the job site design had various longitudinal gradient or cross slope change, a lot of stakes had to be needed. 3D-MC is a system that can be applied the construction work with variable slope.

There are two types of 3D-MC to obtain the coordinates information., one is using GPS, Global Positioning System, satellite data. The other system is using advanced survey instrument total station. This system is known as LPS, Local Positioning System. This report explains concerning LPS 3D-MC.

Total station is a survey instrument that provides the function to sense the coordinates of machine by measuring the distance and the angle of machine from reference point. And total station can record sensed coordinates data. Total station was developed in the 1980s. After that it was added auto tracking function. With this function, survey work could be done by one-man surveyor. LPS-3D-MC is a automation system at construction work based on the technology of the auto tracking total station.

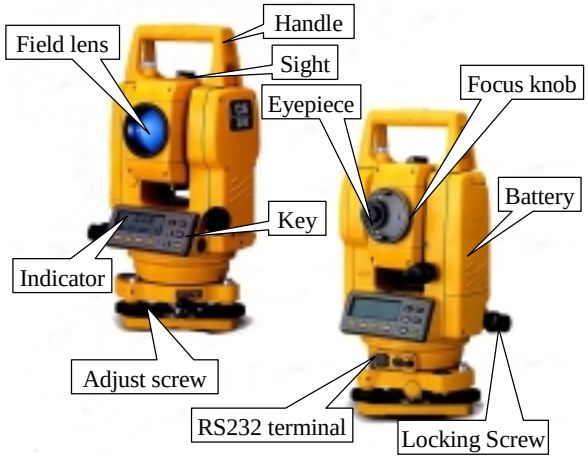


Figure 4. Auto tracking total station

3. OVERVIEW OF 3D-MC

3D-MC, Kajima Road owned, is Topcon made. Topcon is a manufacturer of surveying and optical instrument. The feature of this system is not needed to install a control computer and data communication device in construction machine. Because control laser beam, emitted from total station, provides optical communication function.

System component of 3D-MC grader is shown as figure5. Control process is expressed as follows.

- Total station tracks target prisms fitted on laser receiver on 3D-MC grader, and surveys the coordinates of 3D-MC grader.

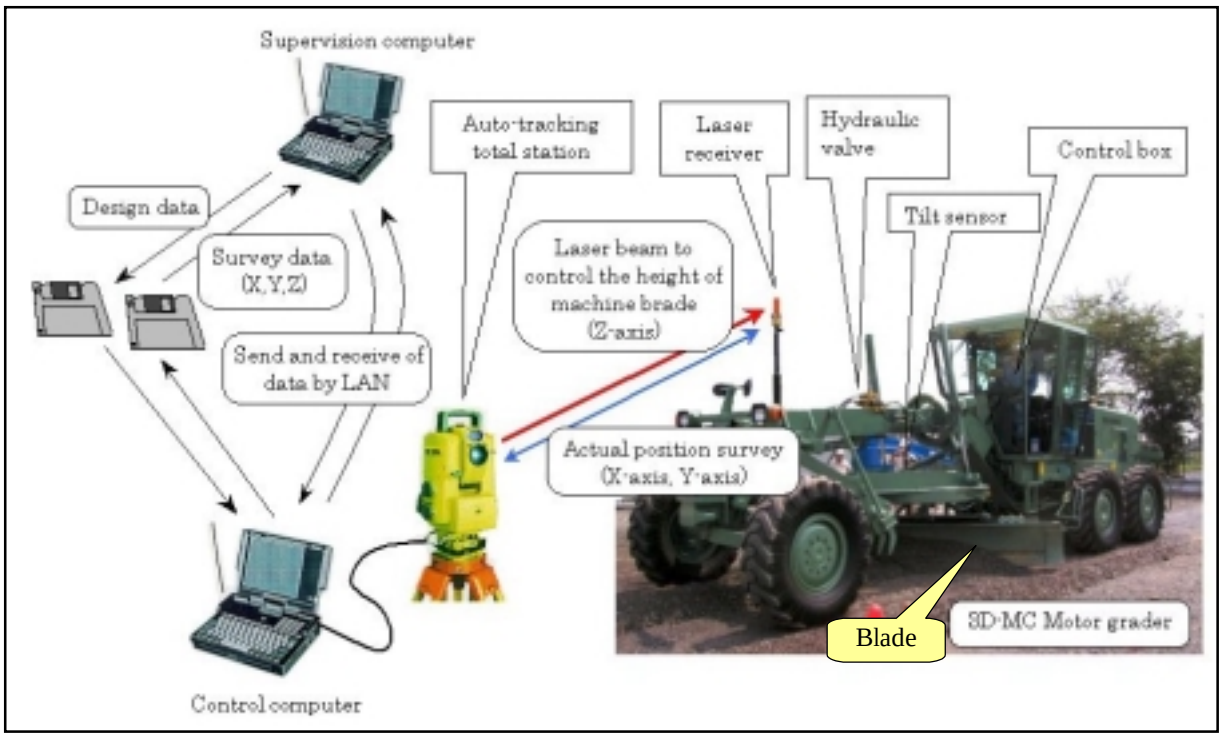


Figure 5. Component of 3D-MC grader

- Total station extracts height and slope data these are consisted with the surveyed coordinates from control computer.
- These data are sent as optical communication on laser beam emitted from total station to laser receiver on 3D-MC grader.
- A blade, actuator of 3D-MC grader, is controlled its height and gradient consisted with the data from transferred total station.

By this means, design data controls construction machine directly. Therefore there is no need to set stakes. And surveyor gets his work easier or burden of operator is much reduced.

4. FUNCTION OF 3D-MC COMPONENTS

3D-MC grader's system flow chart is shown as Figure6.
Main components of this system are explained below.

(1) Auto tracking total station : GRT-2000
Auto tracking total station has been described. It is a main instrument of 3D-MC. Refer figure4.

(2) Laser receiver : LS-2000
Laser receiver is a sensor to receive optical communication data contained laser beam from total station. It transfers the received data to machine control box.

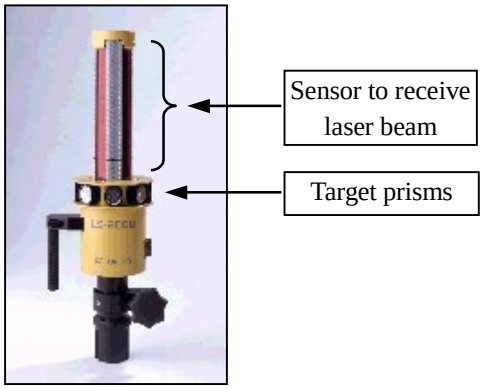


Photo 2. Laser receiver

(3) Machine control box : System five
This is an interface between man and machine, installed in the cabin of grader, provides indicator of the control states of machine. It controls the blade with transferred data. Operator can adjust height of the laser receiver or sensitivity of hydraulic response with the dial on this control box.

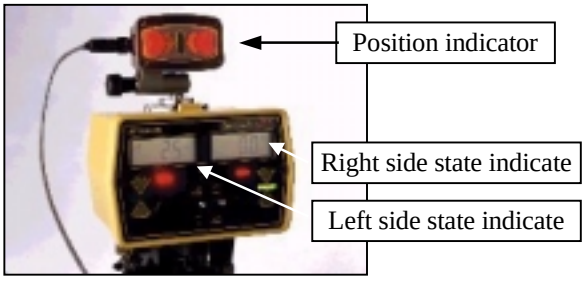


Photo 3. Machine control box

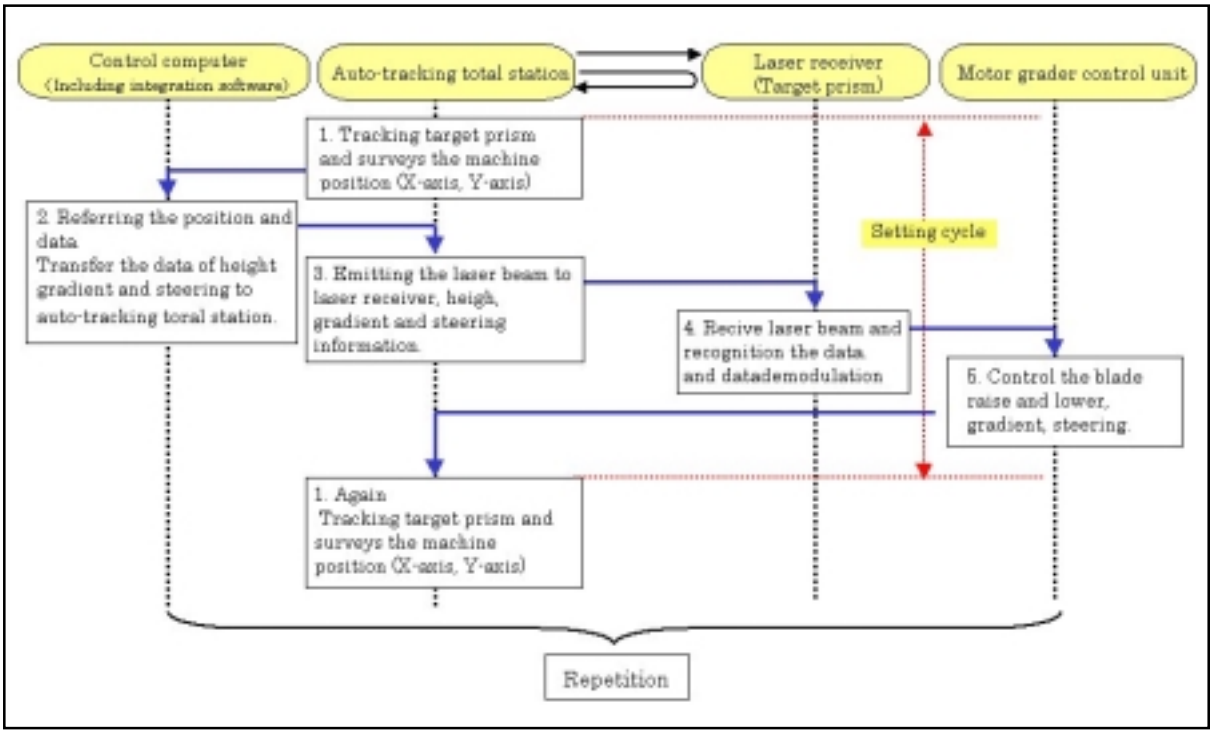


Figure 6. System flow of 3D-MC grader

(4) Software : MS-2000

The control computer is installed 3D-MC special software as MS-2000 that governs 3D-MC. It transfers height and gradient data to total station based on the coordinates data which surveyed by total station.

(5) Control computer : Heavy-duty type

MS-2000 is installed on laptop control computer, connected with total station. It is always brought to job site, so it should be chosen rain proof or dust proof heavy-duty type.

5. OVERVIEW OF TRIAL WORK AND RESULT

5-1. Operation of trial work

Trial work was operated to confirm the accuracy of height and gradient control or responses at inter-section point of cross slope of 3D-MC grader. Trial cases are shown as figure7 and 8.

(1) Trial work : Case1

Setting cross slope superelevation, and separated a few gradient variable area, +2.5%, transition, 0.0%, transition, and -2.5% area.

Such case, rapid change of slope like trial work, is not exist in the actual work. But needed to confirm the response of the actuator.

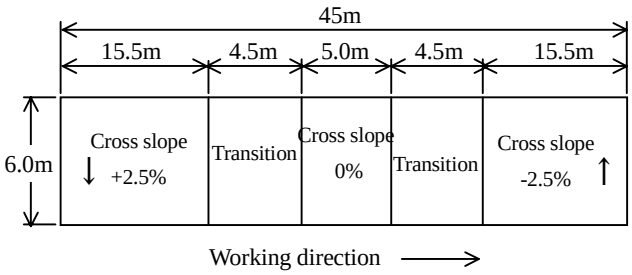


Figure 7. Trail yard : Case 1

(2) Trial work : Case2

The other trial work, amphi-gradiedt cross slope was set. Area is 0.0%, transition, and +-2.0 amphi-gradient. Also confirmed behavior of controlled blade.

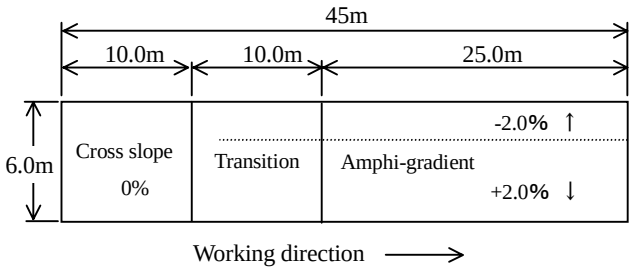


Figure 8. Trial yard : Case 2

5-2. Result of trial work

(1) Accuracy of height level

The result of accuracy of height level is shown as table1. Average of the accuracy of height level was +-2.0mm, even the most difference was within +-15.0mm. Such result was almost same or better than human control. We found one important thing, the value of dead-band affects the result of height level. Setting appropriate value of dead-band brought high accuracy.

	Cross slope	Average	Maximum	Minimum
Case 1	+2.5%	0	11	-9
	0.0%	0	8	-11
	-2.5%	5	15	-3
	Total	2	15	-11
Case 2	0.0%	-7	6	-14
	Amphi-gradient	0	13	-8
	Total	-2	13	-14

(Unit : mm)

Table 1. Accuracy of height level

(2) Sensing of the broken line of amphi-gradient

Software MS-2000 calculates where the center point of the blade is, with surveyed coordinates, and tries to control the blade of 3D-MC grader fits on designed gradient. This control is decided with the position of the center point of the blade, not the position of laser receiver. In the case2, it function was confirmed and controlled better. Figure9 shows this control image.

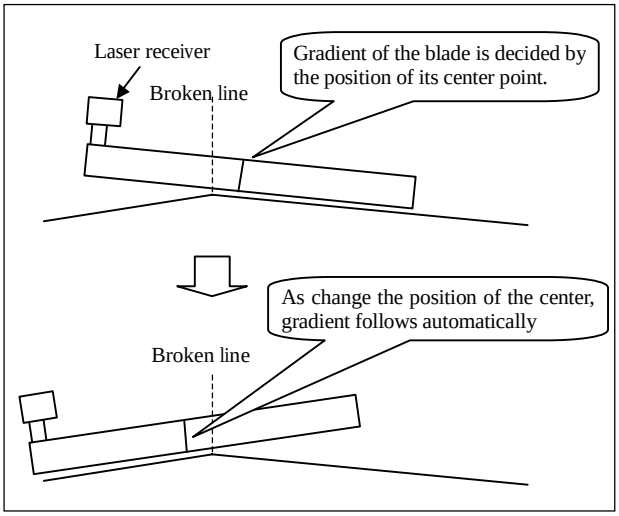


Figure 9. Control image on the broken line

6. APPLIED TO THE ACTUAL WORK

Based on the result of trial work, 3D-MC grader was applied to the actual work.

(1) Actual job site

- Job site : Expressway in Hokkaido Japan
- Total length : 6,560m
- Square : 135,000m2

(2) Result and effect

After working at actual job site work, we obtained advanced term about 3D-MC grader as follows.

- Increase of the productivity

Productivity was more than 3,000m2 by the day constantly. Or more than 4,000m2 productivity was achieved in case of an area with better condition.

By the way, ordinary way of human control was about 2,500m2 productivity by the day.

- Increase of accuracy

Existing method of measuring the height level was done with stakes, therefore measuring points were only stake set points. So the height level between stake and stake were nobody's measurement, accuracy of these interval was depend upon operator's ability. Figure10 shows the image of this relation.

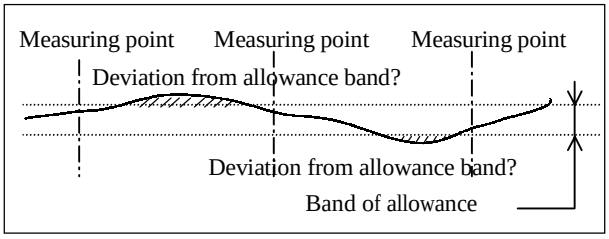


Figure 10. Relation between Height level and allowed band by manual control

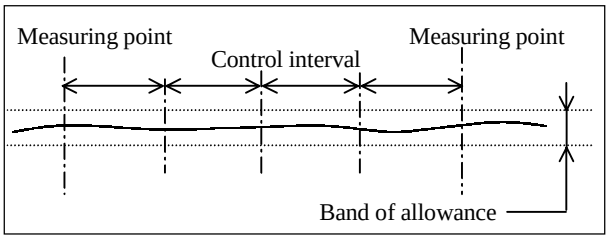


Figure 11. Relation between Height level and allowed band by 3D-MC

3D-MC grader was able to obtain high accuracy of the height level continuously by just once confirm-ation of height level with any stake. In the case of this job site, more than 80% measured point was within +-10mm. This result suggests the possibility for reduction of stakes in the job site and brings the rationality to the next job stage.

Photo 4. Job site work of 3D-MC grader

● Easy adjustment of height control

Operator was able to adjust the height level of the blade in millimeter unit with seeing the indicator of control box, without his intuition.

● Laborsaving and safety improvement

Working by 3D-MC grader was able to reduce the height level measurement, which realized labor-saving. Laborsaving affect to prevent the accident like labor gets hit by machine.

● Unification of data management.

By using 3D-MC, unification of data management was realized.

As same as grader, bulldozer or asphalt paver can be installed 3D-MC to achieve each individual work and can be controlled same design data.

Photo 5. 3D-MC bull-dozer at dam construction

Photo 6. Paving work of 3D-MC asphalt finisher

7. CONCLUSION

We were able to confirm the advantage of 3D-MC.

At the job site, there was a thing worthy mention. An expert operator of grader told he had never seen such superior evenness by grader's work. Which had been worked by 3D-MC grader.

His praise expressed the advantage of this system justly. Hereafter, by applied 3D-MC to various job sites to bring rationalization and we would like to contribute to the lack of veteran operator.

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NEW TUNNELING INFORMATION SYSTEM AND ITS APPLICATION TO ROAD TUNNEL CONSTRUCTION SITES IN KOREA

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Abstract: Ground and rock mass considered in tunnelling have characteristics such as uncertainty, heterogeneity and structural complexity because they have been formed undergoing various geological events for a long period. So, it is difficult for engineers to predict behaviors of rock mass in tunneling. In the paper the authors describe the development of an integrated expert system prototype for site investigation, design and construction in tunnelling and introduce the case applying this system to the tunnel construction site under construction. Geostructure Research Group in Korea Institute of Construction Technology (KICT) has developed the system during the past 4 years. The system mainly consists of several modules which is related to the design, construction and management of tunnelling. The test site, Neung-dong tunnel is located in Ulsan, Korea. The geology map shows it may confront big fault zone whose width is over kilometres. With the networking system of ITIS, various information of face mapping, monitoring and other construction task can be transmitted into the database and GIS Server at real time. And necessary analyses can be carried out with the modules equipped in the system.

Keywords: tunnel, database, GIS, real time, artificial neural network, virtual reality.

1. INTRODUCTION

In general, experiences play the most important role in construction of geotechnical engineering structures such as a tunnel. The reason for this is due to the difficulty of gathering sufficient information on the geology and evaluating the true mechanical behavior of the ground at the design stage. And geological information is generally difficult to quantify because of imprecise and incomplete data observation. With insufficient information on the geology and the mechanical behavior of the ground the tunnel design is carried out.

The concept of 3-D visualization system certainly gives a new aspect in the field of geotechnical engineering. The analysis and interpretation with attention to geotechnical or geological data using 3-D visualization techniques are valid to understand geotechnical site characteristics. Furthermore, the adequate analysis prevents construction delay and additional cost and leads to minimize geological and geotechnical uncertainties.

As 3-D visualization system has become popular in recent years, the authors have started to investigate how to systemize the experiences and decision making procedures of experts in tunnel design and construction by using the 3-D visualization technique, artificial intelligence (AI) and database (D/B) system since 1999. A national research laboratory (NRL) was established for developing the Intelligent Tunneling Information System (ITIS) in September 1999. As a result of 4 years studies, the prototype system consisting of several modules was developed. The modules are (1) visualization module for ground data and structure, (2) analysis module for stability of tunnel, (3) field data acquisition system (4) selection module for tunnel reinforcement, (5) prediction module for face failure, (6) tunnel monitoring system and (7) Virtual Reality (VR) for visualization of tunnel construction. In the paper, the authors introduce the overview of ITIS such as the features and the functionality for analysis and interpretation. Also, the application of some modules on the tunnel site under construction in Korea is introduced.

2. ITIS System Outline

Geotechnical site investigation, tunnel design and construction data are generally existed in forms of manually completed documents, project reports, regional geotechnical maps and geotechnical relational database, etc. And the analysis of these data that located against some form of map or plan is generally two dimensions. ITIS is an integrated D/B management, analysis and visualization system for geotechnical projects especially in tunneling. It provides the environment that makes much easier to create 3-D subsurface model and analysis results and creates presentation-quality.

In developing ITIS the important considerations are easy-operating environment and PC-Windows-based for civil engineers who have antiquated computing capabilities. Using the graphical user interface, the user can operate the system with the mouse and the keyboard. The system consists of input, output, and analysis/interpretation modules. There are a lot of

input data available such as basic geological information acquired from borehole, field investigation and geophysical exploration, in situ test, laboratory test, pre-investigated reports and tunnel initialization information, including start and endpoints. These data are managed and analyzed in a lump to make a 3-D model and several types of analysis with adapting mathematical and scientific algorithms.

Within the system it is possible to zoom, move, rotate, cut, select a gradient and custom coloring, and copy/paste directly to other Windows compatible software. The user can take cross sections in all directions and create subsurface profiles in the cross sections. All of cross sections created are easily compared with each other.

Using the report functionality, the user can get most of the requested information. The extensive pre-prepared report formats are available. Furthermore, the query options can be used to generate lists of data that exist within the database. These can be exported as a pre-prepared files.

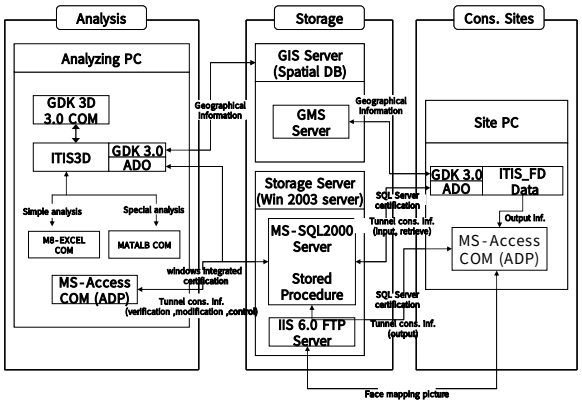

Figure 1. ITIS system outline

Figure 2. ITIS graphical user interface with 3-D windows

3. Modules of ITIS

Visualization module for ground data and structure

The module allows engineers and scientists to input, edit and manage data, and create 3-D models easily. Once logged on to the system, the user meets the Graphical User Interface (GUI). The GUI comprises two units. One enables the user to use all the functions such as file management, digital map editing, data input and analysis, drawing, setting of options, and help. The other is used for creating 2-D and 3-D models with selecting projects. It is possible to zoom, measure scaled distances, drag, select layers, and copy/paste directly to other compatible programs. This module treats most of the data observed and measured in site investigation.

- Three-dimensional geomorphologic data (x, y coordinates and elevation)
- Borehole location and depths of samples and stratigraphic samples taken in borings
- Physical property and other attribute data measured at outcrops
- In Situ and laboratory test results
- Tunnel initialization information, including start and endpoints

The user manages systematically all the data that the user wants to include in the project by using Object-oriented database system (OODB).

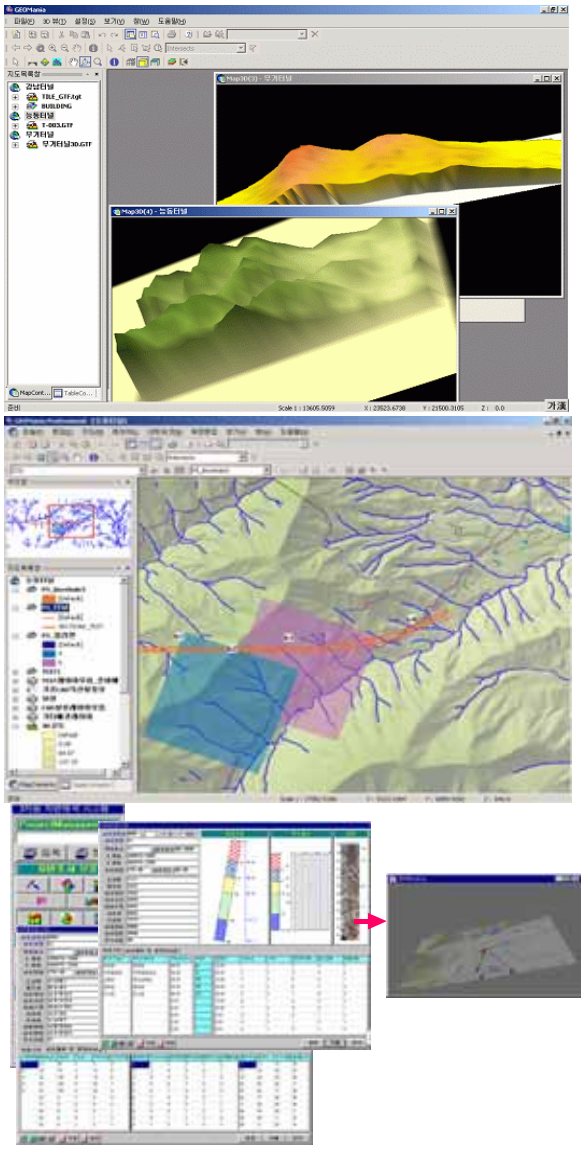

Figure 3. 3D model of Neung-dong tunnel in Korea

3.1 Tunnel Face Information

One of the important parameters influencing the stability of tunnel construction is the information of tunnel face acquired from the excavation steps. The ITIS system can accumulate the database on information of tunnel face mapping during tunnel construction and visualize it 3-dimensionally for the purpose of predicting the state of ground and the geological structure ahead of excavation. Users can access the accumulated database easily and compare the information with the current state of tunnel face. Tunnel face mapping database is mainly composed of two different GUI according to the geological state of tunnel. In the case of soil ground, the fields in the database are filled with ground condition and reinforcement rather than discontinuities and classification of ground. But in the case of rock mass, various items related with rock mass characteristics are very important factors. Figure. 2 shows the sample data of tunnel face mapping database in Neung-dong tunnel.

Figure. 4 tunnel face maaping example of Neung-dong tunnel in Korea

3.2 Management of Monitoring

During tunnel excavation a systematic monitoring is important for the determination of support type and quantity, as well as for controlling the tunnel stability. Geodetic methods of absolute displacement monitoring allow determining the spatial displacement vector of each measured point. During the tunnel construction, daily general monitoring and special monitoring are carried out at the station of tunnel face. And after the construction is finished, monitoring for maintain and management of tunnel is planned to be performed. Special monitoring items are axial force of rock bolt, shotcrete stress, ground displacement and 3-dimensional displacement. Each item has its own database table and all items are connected with one another throught the key field, face station. Figure 5 shows windows of database system for monitoring.

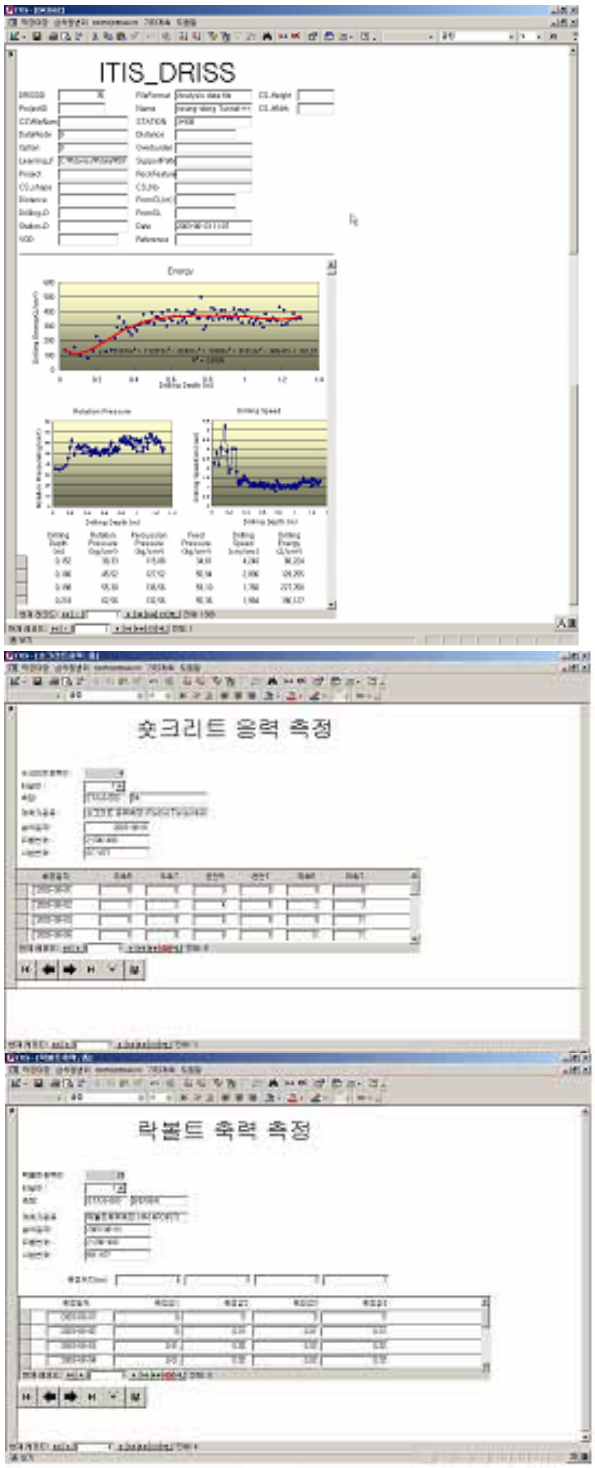

Figure 5. Database system for monitoring

3.3 VR for visualization of tunnel construction

Technology is providing engineers and geologist with new and interactive ways to model the design and construction of tunnel. The virtual environment, in which the visualization of the design and construction progress is effected, shows to be ideal for simulating geological features, the predicted results for ground surface settlement and face failure. The system prototype has been tested on the tunnel construction site. Figure 6 shows examples of the prototype system's outputs. The recent VR techniques are extended to connecting with GIS D/B. It will be more powerful tool that gives rise to many civil engineering fields including tunnel engineering to adopt this technique as computer hardware industry grows rapidly.

Figure 6. VR screen shots of the portal in tunnel and wedge failure.

4. CONCLUSIONS

The authors have developed Intelligent Tunneling Infor-mation System (called ITIS) that is an integrated expert system including visualization, evaluation and prediction technology of tunnel survey, design, construction and reinforcement system based on D/B, Artificial Intelligence, 3-D visualization and Virtual Reality technologies. And the system is applied to the tunnel site under construction, which will be benefit for engineers who do not have sufficient knowledge or experience in tunnel construction.
The system will be extended continuously with several additional modules as a National Research Laboratory (NRL) Project in Korea.

ACKNOWLEDGEMENT

This research has been performed as a part of the National Research Laboratory project provided by KMOST(Korea Ministry of Science & Technology). The authors greatly appreciate their financial support.

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FUZZY LOGIC APPROACH FOR THE DESIGN OF REINFORCEMENT IN TUNNEL EXCAVATION

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Abstract: Specification of reinforcement method was suggested according to the ground condition and tunnelling environment such as adjacent building and surface settlement. Tunnel database consists of 8 different groups of data according to the tunnel construction situations and major problems of ground. A tunnel countermeasure expert system based on client/server system was developed with on-line. The expert system provides proper solution to the each construction sites backing up the information of the tunnelling and ground information through Internet. The effective factors of tunnel construction were shown by the analyzing relationship and partial relationship between face stability and RMR factors. This study will be very helpful to make the most of in-situ data and suggest proper applicability of tunnel reinforcement system escaping from the dependence of some experienced experts for the absent of guide.

Keywords: tunnel failure, countermeasure, fuzzy quantification II theory, tunnel reinforcement design.

1. INTRODUCTION

Many studies of tunnel and tunnelling safety have been done based on the increasing social interests in underground space since 1990's in Korea. Increasing the construction of tunnel, it is important to define the cause of the abnormal phenomenon and then to carry out the countermeasure against the major cause. Especially, proper countermeasure for the unexpected and difficult excavation is urgently needed in the case of tunnelling site constructed in urban area. Although technological development of tunnel engineering has been accelerated consistently, there has been no clear specification of reinforcement method for the unstable tunnel situation in Korea.

In this study, a lot of types of tunnel failure and their countermeasure methods were surveyed, then the specification of countermeasure was suggested according to the ground condition and tunnelling environment such as adjacent building and surface settlement. A tunnel countermeasure expert system based on client/server system was developed with on-line database. The expert system provides proper solution to the each construction sites backing up the information of the tunnelling and ground information by internet.

This study will be very helpful to make the most of in-situ data and suggest proper applicability of tunnel reinforcement system escaping from the dependence of some experienced experts for the absent of guide.

2. Modified Takagi-Sugeno (TS) Fuzzy Model

On actual sites, the engineers often have to begin to cope with the safety problem while the cause is still unknown. However, the selection of counter measure is not easy because there are many unexpected problems and uncertainties of ground. In this study, many types of tunnel failure were surveyed and the detail causes were studied for brief countermeasure. Then, the expert system using fuzzy inference rule was developed (Chikahisa et al.1997).

The record of Tunnel failure and collapse throughout Korea has been established and 21 significant incidents are documented in this study. Especially, subway tunnels including second stage of Seoul subway, road tunnels and express railway tunnels have been analyzed. This data shows that these incidents, particularly in soft ground in urban areas, may, when they occur, result in major consequences not just to those working in the tunnel but to members of the public, the infrastructure and the built environment.

The 10 significant collapses and outlines of the circumstances of the incident were investigated during second stage of Seoul subway, and 11 major collapse incidents among the various tunnel sites were studied since 1993. Among those 21 incidents, 8 sites were surface collapse and large collapses more than 50m2 were 5 cases. 14 incidents were occurred in urban areas and three in road tunnel and one in express railway tunnel (Kim et al. 2000).

Kim et al. (2000) analyzed the main cause factors of the collapsed tunnel analyzing the relationship between collapsed cases and their ground conditions. Especially, RMR classification items suggested by Bieniawski were considered because it is usually applied in-situ site of Korea. 20 significant incident sites are separated from 52 tunnel failure data and studied about water inflow, depth, rock type, joint,

alteration and so on. Abroad failure tunnels surveyed by Cecil (1963), whose total length is approximately 67km and which contain 14 projects and 97 sections are analyzed as well.

3. Expert System for Tunnel Reinforcement

According to the record of tunnel incidents above, proper countermeasure system is urgently needed so that the expert system was studied to predict the safety of tunnel and choose proper tunnel reinforcement method using fuzzy quantification theory and fuzzy inference rule based on tunnel information database (Watada et al. 1982). Using fuzzy theory, fuzzy membership function is composed and tunnel safety level is inferred through the membership function. After the tunnel safety level is graded, proper tunnel reinforcement is selected. This expert system is purposed to help the engineers to make a decision of counter measure against unexpected situation providing proper judgment criteria applying the fuzzy theory. Each observed items and tunnel face mapping data are changed to fuzzy set and tunnel reinforcement applicability has been inferred. To establish the membership function is the most important and difficult part of fuzzy inference system because of the absence of experienced engineers and lack of data. Quantification theory was used for building membership function as an alternative method (Kim et al. 2000). The membership function consists of more objective data through the application of quantification theory, which gives weight value to tunnel quality data. Tunnel safety set to be the independent criterion and the items of tunnel information database set to the subordinate variables and then, the fuzzy inference rule is predicted.

3.1 Overview Fuzzy inference system

Fuzzy sets were introduced by Zadeh as an approach to handling vagueness or uncertainty and, in particular, linguistic variables. Classical set theory allows for an object to be either a member of the set or excluded from the set. This, in many applications, is unsatisfactory since, for example, if one has the set that describes all males who are tall as those whose height is greater than 5'8" then a 6'0" male is a member of the set. A male whose height is 5'7 ", however, is not a member of the set. This implies that a man who is " shorter than another tall man is not tall.

By the same token this approach does not differentiate between members. Michael Jordan (6'8") and Bob John (5'11") are both equally members of the set `tall'. Although this appears at face value to be a trivial example there are many domains where this approach is of little use. Fuzzy sets differ from classical sets in that they allow for an object to be a partial member of a set. So, for example, John may be a member of the set `tall' to degree 0.8. He is tall to degree 0.8. Fuzzy sets are defined by a membership function. For any fuzzy set A the function represent the membership function for which indicates the degree of membership that x, of the universal set X, belongs to set A and is, usually, expressed as a number between 0 and 1.

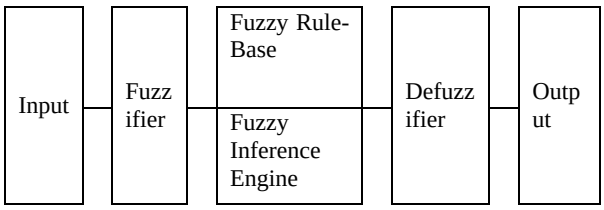

Figure 1. Diagram of fuzzy inference

Fuzzy theory has been applied to describe ambiguous data in many filed include engineering fields. Fuzzy set is used for fuzzy inference and the process of inference is introduced in Figure 1. After fuzzification of the input data, Fuzzy inference is done based on the fuzzy rule, then output comes through defuzzification of the inference values.

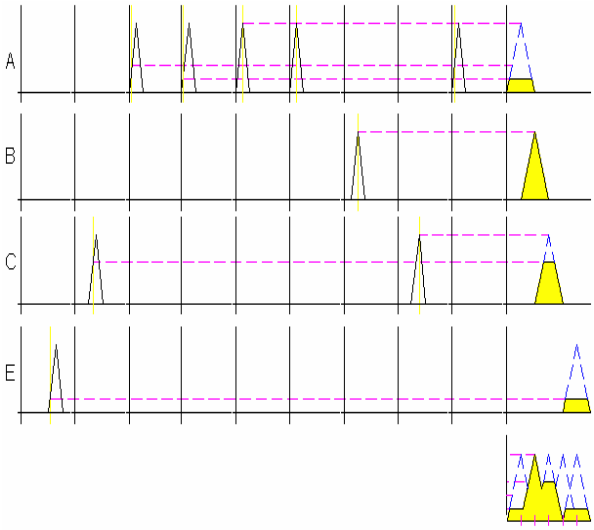

Figure 2. Fuzzy inference processing

Fuzzy reasoning needs fuzzy rule. If the rule, “IF x is A then y is B” were given, y is to be inferred with the condition of the input information, “x is A”. Fuzzy rule is expressed IF-THEN form and consists of pre-condition proposition and post-condition proposition.

3.2 Tunnel face mapping D/B

D/B for this expert system consists of 8 groups whose characteristics of tunnel construction is different. Table 1 shows explanation of each database group such as special ground condition or major concerning of tunneling. The standard of division is based on the major situation of tunneling in Korea.

Table 1. Tunnel face mapping information for D/B

D/B	Site	No. of face	Length (m)
Under river	River Han	133	460
Fault zone	Pusan subway	330	600
Weathered rock and sand soil	Seoul subway station 6-00	97	200
	Seoul subway station 6-00	60	50
Weathered rock	Seoul subway station 5-00	91	118
Alluvial near river	Seoul subway station 5-00	154	338
Ground Structure	Seoul subway station 5-00	59	106
Underground structure	Seoul subway station 5-00	67	436
Fault zone & Gneiss	Road tunnel	170	450

3.3 Constitution of inference system

This inference system has two main parts. First part decides tunnel information input items based on the tunnel face mapping information data easily obtained in-situ site. In this stage, using fuzzy quantification theory Ⅱ, fuzzy membership function is composed and tunnel safety level is inferred. After tunnel safety level is predicted in first module, fuzzy inference rule is arranged between safety level and countermeasure method, then proper applicability of tunnel reinforcement is selected from post-module tunnel information database.

Tunnel information database consists of major face mapping items and tunnel safety effect factors such as adjacent building and overburden above tunnel, but in this system, only face mapping data expressed 4 levels was used. Main input data was made of uni-axial strength, RQD, joint spacing, joint condition, joint direction and water inflow included to RMR classification commonly adapted in Korea. First membership function built by correlation coefficient evaluates the safety level of tunnel face in Figure 3. Input module of tunnel reinforcement database showed in Figure 4 has eight items mostly used major collapsed sites and it consists of face shotcrete, ringcut excavation, mechanical excavation, forepoling, L.W grouting, bench shorten, invert and steel pipe grouting. As shown in Figure 5, membership for the applicability of each reinforcement method was built and the grade was calculated by defuzzification using centroid method. Fuzzy inference rule between each group of data and reinforcement methods shows in Table 2.

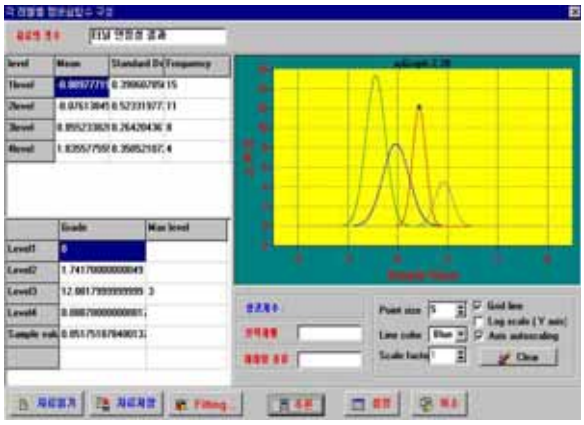

Figure 3. Membership function of safety evaluation of tunnel face

Figure 4. Tunnel Reinforcement database

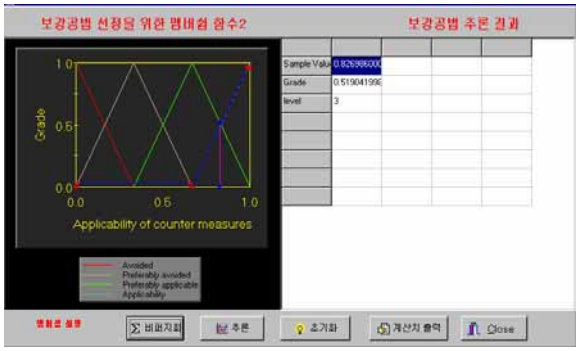

Figure 5. Membership function of reinforcement

Table 2. Fuzzy inference rule of Seoul subway (Station 5-18)

No. of face	1	2	3	4
First membership grade				
Level A	0.96	0.09	0	0
Level B	0.04	0.91	0.98	0.01
Level C	0	0	0.02	0.99
Level D	0	0	0	0

Fuzzy inference rule				
Face shocrete	0.18	0.63	0.67	0.88
Steel pipe grouting	0.67	0.67	0.67	0.88
Ringcut	0.14	0.33	0.34	0.87
Mechanical excavation	0.14	0.33	0.34	0.87
L.W grouting	0.35	0.74	0.86	0.12
Invert	0.18	0.63	0.67	0.88
Bench shorten	0.18	0.63	0.67	0.88
Forepoling	0.16	0.78	0.89	0.89

Figure 6. Inference result of reinforcement applicability

The comparison results between the predicted applicability by reinforcement system and measured data were very similar. In-situ data were obtained in eight tunnel sites as shown in Table 1. There is inference result of eight reinforcement methods used in Seoul subway tunnel in Figure 6. In the case of Seoul subway tunnel under the river Han, 104 sections were used for building database among 133 face mapping data, then the system was tested with other 29 sections. This system will be very helpful to make the most of in-situ data and suggest proper applicability of tunnel reinforcement system escaping from the dependence of some experienced experts for the absent of guide.

3.4 Additional decision-making

After evaluating the applicability of each reinforcement method by fuzzy inference system, user can be provided a simple pattern of selecting methods with more specific data of tunneling such as details of ground condition and occurring problems. Ground condition consists of seven items as shown in Table 3 and the levels were defined according to the opinion of experienced experts and construction results in Korea. Problems of excavation are composed of five items and each problem has countermeasure methods shown in Table 4. The relationship between each problem and its countermeasure is based on the Korea specification and opinions of experts. Table 5 shows the pattern of suggestion method for the given 2 input data.

Table 3. Details of ground condition

Items	Level
Depth	less than 1.0D 1.0 - 1.5D 1.5D - 3D More than 3D
Ground Classification	Sediment Weathered soil Weathered rock Soft rock Moderate rock
Fault Zone	Yes No
Location of Fault zone	On the face crown lower than 0.5D 0.5 ~ 1.5D higher than 1.5D
Overburden	Calculation
Inflow	Dry (10～25ℓ/min) (25～125ℓ/min) (>125ℓ/min)
Location of Groundwater	Over SL, Below SL

Expert system will provide construction site direct countermeasure method for the unexpected problems via on-line. Selecting similar ground condition among the 8 data group, Proper reinforcement is suggested and similar construction pattern, which was used in other sits, will be very helpful in decision-making.

Table 4. Problems of excavation

Items	Level	Countermeasure
Overburden	< 1.0 D 1.0 - 1.5 D 1.5 D - 3 D > 3 D	Forepoling, Umbrella arch, Ringcut, Jet grouting, Piperoof
Inflow	RMR	Chemical grouting
Face stability	Fuzzy level	Face shotcret, invert, ringcut, bench shoten, Face rockbolt
Adjacent Building	On the face crown < 0.5 D 0.5 ~ 1.5 D > 1.5 D	Piperoof, forepoling, umbrella arch method, Jet grouting
Surface settlement	Neural network inference	Piperoof, Jet grouting, umbrella arch method, Invert

Table 5. Suggested pattern of reinforcement

Method	Forepoling
Purpose	Sealing of fault zone and reinforcement of around tunnel face
Design Pattern	L=12 m 2 colums overlab
Others	More than 5 hole into the tunnel face
Warning	If upper alluvial layer comes close to 1 m, reinforcement required

The data used in this study were obtained form the various tunnel construction sites in South Korea. They consisted of laboratory tests and engineering rock mass classification. They are specific gravity, absorption ratio, P and S wave velocities, uniaxial compressive strength, elastic modulus, Poisson's ratio of intact rock, tensile strength, cohesion and friction angle by triaxial compressive test in the laboratory test. They also include RMR and Q values. It is possible to have different influences on rock mass properties even in the same RMR values with the different combinations of six RMR ratings. So separate ratings except for adjustment according to joint orientation were included as input variables for fuzzy model. And output variables were deformation modulus, cohesion and friction angle widely used in numerical analysis. These input and output variables are tabulated in Table 1.

3.5 Training and validation data

A total number of 107 data obtained from the domestic tunnel construction sites were randomly divided into four sets of 25% of total data. And each set had 26 or 27 records (27+27+27+26=107). The three sets (75%) were used for training of fuzzy model and the other set (25%) was used for validation of it, which meant that there were four possible fuzzy models in each prediction of engineering rock mass property. The reason for doing this was to see how much variation there were in accordance with the distributions of training and validation data. The names of fuzzy models are tabulated in Table 2. Also the data used here was scaled between 0 and 1, which reduced the time for calculation and effect induced by different measured units in each parameter.

3.6 Criteria for the selection of model

Modified TS fuzzy models were trained until they satisfied the criteria as increasing the number of clusters of input data. The indices used for the criteria were RMSE (Root Mean Squared Error) and the rate. Rate is the change of RMSE in each training stage defined by Chen (1998) shown below.

Table 3. Input (X) and output (Y) parameters and their ranges for fuzzy model.

	Parameters	Range
X1	Specific gravity	0 - 5
X2	Absorption ratio (%)	0 - 12
X3	P-wave velocity (m/s)	0 - 8000
X4	S-wave velocity (m/s)	0 - 5000
X5	Uniaxial compressive strength (MPa)	0 - 500
X6	Elastic modulus (GPa)	0 - 20
X7	Poisson's ratio	0 - 0.5
X8	Tensile strength (MPa)	0 - 50
X9	Cohesion (MPa)	0 - 50
X10	Friction angle (Deg)	0 - 90
X11	RQD	0 - 100
X12	RMR-1 (uniaxial compressive strength)	0 - 15
X13	RMR-2 (RQD)	0 - 20
X14	RMR-3 (spacing of discontinuities)	0 - 20
X15	RMR-4 (condition of discontinuities)	0 - 30
X16	RMR-5 (ground water)	0 - 15
X17	RMR	0 - 100
X18	Q	0 - 1000
Y1	Deformation modulus (GPa)	0 - 30
Y2	Cohesion (MPa)	0 - 20
Y3	Friction angle (Deg)	0 - 90

$$RMSE = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(y_k - \hat{y}_k)^2} \quad (1)$$

$$Rate = \frac{\left|RMSE - RMSE(0)\right|}{RMSE} \quad (2)$$

4. Inference Results

Based on the tunnel face mapping database, relationship and partial relationship between face stability and RMR factors were analyzed. Partial relationship coefficient means the strength of effectiveness of each factor to face stability when other items are fixed. Relationship coefficient between face stability and RMR items of 8 database groups is shown in Figure 7 and there are various differences among the groups of data according to property of construction situation.

As shown in Figure 8, partial relationship coefficients of 8 data groups between face stability and RMR items are various and it means that major effective factor of face stability is not same in all tunnels. In the same way, the relationship between face stability and the applicability of reinforcement methods was analyzed. Relationship coefficient shows that appropriate reinforcement methods should be considered differently according to the group of data because each database has different property of ground or construction problem. It means that each tunneling face needs different countermeasure method depending on the property of tunneling situation and problem.

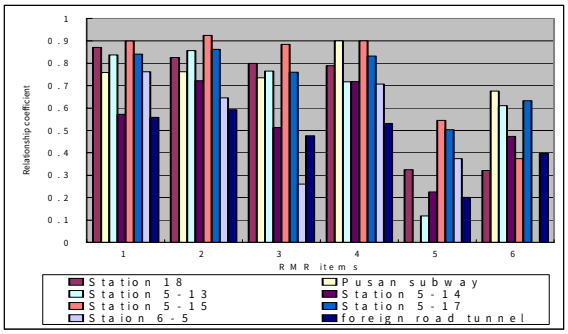

Figure 7. Relationship coeficient between face stabili ty and RMR items

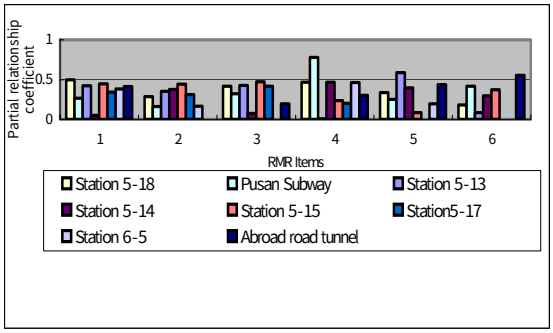

Figure 8. Partial relationship coefficient between face stability and RMR items

5. Conclusions

In this study, after tunnel collapsed incidents were surveyed and the detail causes were analyzed, the expert system for tunnel reinforcement selection was presented. Database is divided to 8 different data group according to the properties of tunneling construction and major problem of excavation because each data group provides different inference results from each particular condition. From this the following suggestions were made for better understanding of the tunnel reinforcement system.

Prototype of the expert system was developed to evaluate of tunnel safety and select proper reinforcement method based on the fuzzy theory after building tunnel information Database.

The expert system developed in this study has been tested on 8 in-situ sites including the river Han subway tunnel considered one of the most difficult construction sites and needed various reinforcement methods. Its applicability has been confirmed by comparison of inferred results and field data.

There are some different among the correlation coefficients between RMR factors, which used as tunnel face observation items, and tunnel safety level according to the in-situ sites. Partial correlation coefficients are various as well. It verified that face mapping items may be considered differently at each site.

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MODELING MEASUREMENTS AND MEASURING MODELS – PROBLEMS AND SOLUTIONS OF 3-D GEOMETRICAL CONTROL IN CONCRETE BRIDGE ENGINEERING

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Abstract: The paper introduces a model and procedure of 3-D geometric process for concrete bridge engineering. New 3-D CAD design tools and 3-D measurement methods were developed and tested in the several real bridge construction projects in Finland during 2001-2004. The paper describes these observations and suggests the first conclusions for future developments as well as more expansive utilization especially in bridge construction in Finland.

Keywords: concrete bridge design, 3-D CAD, 3-D measurements

1. INTRODUCTION

One of the key problems in concrete bridge engineering is the information break between design office and site measurements. Another key problem is the use of 2-D design methods and drawing CAD tools for design instead of advanced 3-D modeling possibilities. In the paper this problem and its development possibilities are considered based on the results of an R & D project "Intelligent Bridge" carried out in Finland 2001-2004.

2. MODELLING THE DESIGN AND MEASUREMENT PROCESS OF BRIDGE ENGINEERING

In the project MicroStation was used as a software environment for the application development. New 3-D modeling methods were developed and tested. The determined new CAD tools were programmed by utilizing the newest 3-D modeling features of MicroStation. The most essential working applications are different extrusion tools, with which most of the different types of bridge parts can be modeled. The functionality of the 3-D design and measurement systems was tested through several real bridge projects in Finland during 2001-2004. The tests are further continuing.

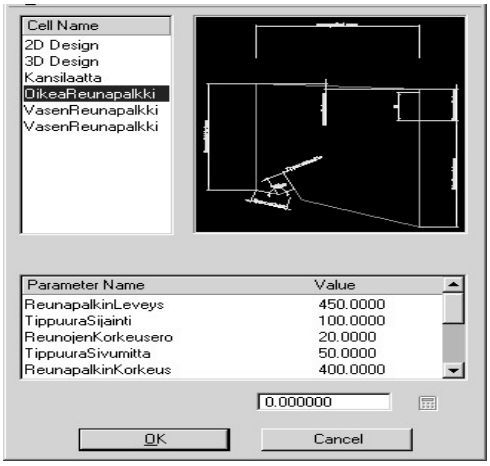

Figure 1. User interface of the 3-D bridge design application: each of different profiles of total bridge structure are separately modeled using 3-D road lines as well as digital terrain model as initial data. The needed dimensions for objects were entered by the aid of parameterized variables.

In the later phase of the process, the designed solid models were directly utilized in site measurements, where robot tachymeters as well as 3-D laser scanners were used. Dimension measurements were tested by using a real-time

connection with the design model. The deformations of concrete structures as well as mould ones were anticipated. First tests were executed by transferring the anticipated coordinates directly to the tachymeters used.

In addition two different methods to generate a superimposed surface or solid structure of bridge were studied. In the control measurements also laser scanners were used. The observed 3-D points and point clouds were transferred and connected to the design model using the same CAD analysis software. Also real-time connection between the site measurements and the design model was used. Finally the measured points and point clouds were analyzed by modeling them, if necessary, into 3-D geometric elements and comparing them to the design models. The 3-D deviations were calculated according to the principles of the bridge tolerances.

3. RESULTS

One of the most essential changes will be happened in concrete bridge design. The change from earlier 2-D drawing-oriented design methods to new 3-D modeling methods with new tools seems however to be quite fluently for designers. On account of the first design cases clear benefit was evaluated to be obtained with the 3-D method already just in the design office.

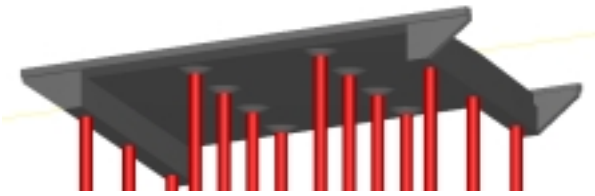

Figure 2. An accurate 3-D solid model of concrete bridge for the next drawing generation and site measurement phases.

Different bridge modeling tools to help bridge designer to work more effective were developed. On account of these tools the most typical concrete bridges having not demanding geometries can be modeled. The cases having complicated variable geometries set always more demands for design. Therefore also more design time will be needed. However, in such cases the benefits of 3-D modeling methods can be more and more utilized.

Figure 3. An example of the points needed in practice for mould construction: the angle lines of mould surfaces by the aid of 3-D points with 2 m intervals.

The next challenge is to transfer 3-D bridge model to control site operations. The Fig. 3 describes a group of the points needed for mould construction. In addition the 3-D lines of the edge beams were needed also with suitable intervals. it is essential that the model of super imposed structure is needed in this working phase. This means that the points must include the anticipations of estimated structure deformations as well as mould deformations during concrete processing. In practice this can be done by changing *z* coordinates of the points. The dimension measurements were executed with a tachymetry.

Figure 4. Controlling the accuracy of bridge mould by Cyrax laser scanner - Varkaus.

The accuracy control of complete mould was executed by Cyrax laser scanner (Fig. 4). The 3-

D point cloud must be compared to the model of super imposed structure.

Figure 5. Controlling the accuracy of concrete bridge structure - Suonenjoki.

The accuracy of complete concrete structure was controlled by Cyrax laser scanner (Fig. 5). In the bridge measurements done in the project, the average work consumption has been about 4 hours per a bridge. In addition, one hour was needed for point clouds registration and if wanted, 2 hours for 3-D modeling of the point clouds with Cyclone tool of the Cyrax system.

Figure 6. Measurement of an old bridge - Tampere.

On interesting test was a measurement of an old bridge, which was decided to be continued (Fig. 6). The surfaces of the bridges were measured by a Cyrax laser scanner. The point clouds were registered together and further modeled by Cyclone. The next phases are the calculation of 3-D deviations of the bridge comparing the point cloud to the bridge design model. This means that the model must be first designed on account of the old 2-D drawings. The next step is then to design the 3-D model of the continued bridge. This will be done during the autumn 2004.

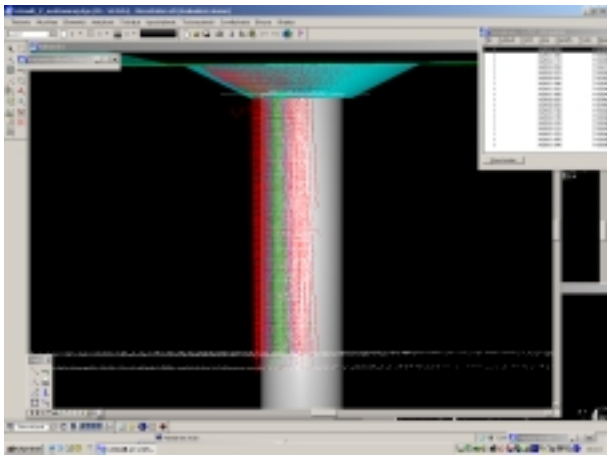

Figure 7. An example of the comparison of point cloud to the solid model of the bridge: the deviations are automatically calculated point by point and further clarified graphically by the aid of different colors. The deviations are the shortest distances from points to the solid.

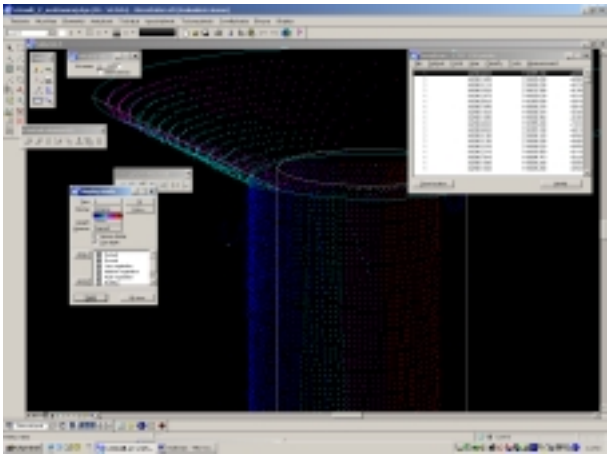

Figure 8. Comparing point cloud to the solid model of column.

4. CONCLUSION

According to the test results this new 3-D concept seems to be very efficient in the domain of concrete bridge engineering. Working in 3-D space was evaluated to decrease design errors. The labor productivity of design work was evaluated to be improved. Still more important was proven to be the possibility to connect models directly to 3-D site measurements. This eliminates transfer errors due to human factors and format conversions.

According to the test the real-time connection between CAD and measurement devices is useful. Its is possible to dimension arbitrary 3-D points to the bridge site and structures. In future it will be also possible to develop more intelligent into real-time measurements. For example, it would be possible to automatically identify the designed coordinates from the solid model on account of the measured coordinates and then calculate the deviations. Also laser scanners with possibility to measure the 3-D forms and dimensions with point clouds seem also to have a very great utilization in bridge engineering. On of the next challenges is the regeneration of the bridge tolerance determinations (SYL specifications) in Finland.

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MODELING INFORMATION FLOWS FOR AUTOMATED ROAD REHABILITATION PROCESS

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Abstract: This paper introduces information flow models for the total process of automated road rehabilitation. Only superstructure layers of roads are considered in this examination. The practical processes and tools used in the common construction processes in Finland and Italy are examined. The purpose is to demonstrate the comprehensive development of automation into rehabilitation processes.

Keywords: Automation, old road structures, rehabilitation.

1. INTRODUCTION

In most industrialized countries, the basic road network has already been built. Therefore, today's challenge is the maintenance of this strategic part of the national wealth. It has been estimated that already 85% of Europe's road construction projects today have different rehabilitation operations. Both in Finland as well as in Italy the activities of road construction have already strongly concentrated on the rehabilitation of old road structures.

Automation is one of the present means for improving the process efficiency and product quality, also in the domain of road rehabilitation. The various latent but achievable benefits of automation will be produced through the total process of construction activities. Automated process means numeric controlled process. In road construction the numeric control of a process must be built on the three-dimensional geometric management of different work operations.

Figure 1. Road rehabilitation process begins with existing road damage – a case in Finland.

Considering the total process of road construction from the automation point of view, we can observe a process consisting of five parts (Fig. 1): 1) initial data measurements, 2) product design, 3) site operations including dimension measurements and machine control operations, and 4) quality control measurements.

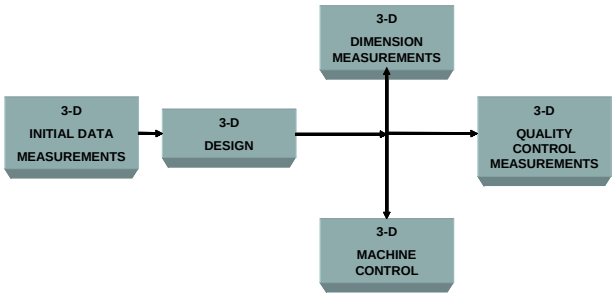

Figure 2. The main work phases of road construction process.

2. ROAD REHABILITATION PROCESS IN FINLAND – STATE OF THE ART

The basic phases of road rehabilitation are road data collection, problem diagnosis, rehabilitation design and dimensioning, construction, and quality control. The survey methods providing the basic information for the rehabilitation design are as follows: a) GPR (ground penetrating radar) for thickness surveys and detecting reasons for damages, b) FWD (falling weight deflectometer) for stiffness measurements of structural layers and subgrade, and c) profilometer or laser scanning techniques to collect information from the road surface. All of these techniques need very accurate positioning systems in order to produce precise 2-D or 3-D road models. Positioning will be much easier in the future through the new national Digiroad GIS data bank system. In addition to the above mentioned survey techniques, sampling is still needed for laboratory analysis and for optimum proportioning of the rehabilitated road structures. In Finland digital video is also used to provide information about the road and its surroundings. After the data collection, the road survey data is analyzed and a problem diagnosis is made using Road Doctor for Win or Road Doctor Designer software packages. In this phase it is also possible to link different types of data, such as pavement distress data and rutting, and also IRI history from the Finra road register and road condition (KURRE) data bases. This search and linking can be made using RDA software developed for Finra. After the cause(s) of the problems for the rehabilitated road have been solved, Road Doctor programs can also be used for the rehabilitation design.

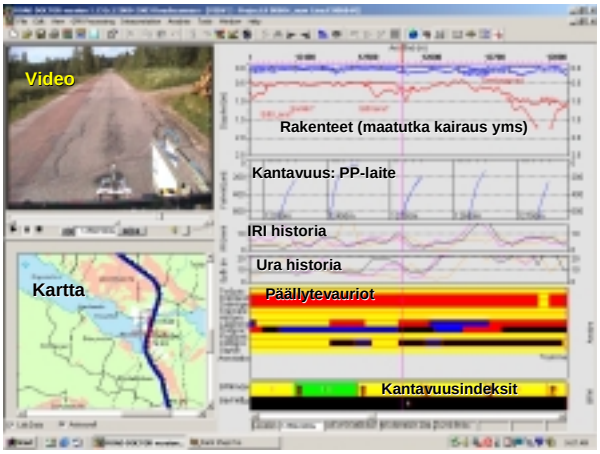

Figure 3. Road Doctor software tool for road rehabilitation design – Finland.

According to the new procurement policy, Finra is now moving towards design and building contracts that allow more innovative solutions for the contractors. That is why Finra has developed an internet version of RDA. This enables contractors to download the road survey data results as well as other technical and commercial contract documents to their own computer systems. After the rehabilitation design has been completed, contractors download the bidding documents back to the Finra database.

Figure 4. The first milling machine in Finland which has been equipped with an automated machine control system.

The current R&D work in Finland is now focusing on transforming the design data for road construction machinery. During the first phase the goal is to transfer the design data from

Road Doctor Designer to cutter and stabilization machines.

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Figure 5. Testing the first Finnish 3-D machine control system for asphalt spreader – Summer 2004 Finland.

3. ROAD REHABILITATION PROCESS IN ITALY– STATE OF THE ART

To illustrate the complete working process, currently used technologies and practices, developed processes, methods, field observations, test results, etc., we prefer to use the Road Cadastre (C.S.) as a guideline. This has a more complex meaning than a Digital Road GIS data bank. A 1992 law instituted the C.S. Then in 1993 the new Highway Code introduced the obligation for the Onwers, motorway companies, national company or agency for statel roads, and regional and local administrations to set up and maintain the C.S., which would manage the road network and program the rehabilitation interventions, while a National Record of roads was set up and managed by the Central Administration. The practical set-up of C.S. began in June of 2001. Within two to five years all roads, from motorways to country roads less than 5.5 meters long, had been recorded. Between 1992 and 2001 many tests and experiments were performed by motorway companies, national agencies, software houses, regional administrations, and universities, in order to have databases with geographical information, maps, images, and all the required data in order to acquire data by GPS, aerophotogrammetry, videocameras, laser scanning, FWD or GPR's, and other methods and systems.

The target of C.S. is to define the inventory of a road's property; to supply support for the management of road property, and to plan its development, particularly for the following: classification of the road, administration management, adjustment projects, maintenance project management, and terrestrial navigation. The C.S. data is the element to which all other information in the data information system must be related. The C.S.'s interests are represented by an "entity function" whose characteristics are described by "attributes". The rules of C.S. specify the entities and their attributes; the global attribute is referred to as the global road, while the split up attributes are related to variable characteristics on the road. Fig. 7 illustrates the attributes of the C.S.

The survey types of these events can be divided into the following groups: 1) survey of structural-functional characteristics, 2) qualitative survey, 3) survey of geometric characteristics, and 4) morphologic survey (Fig.5). The methodologies of the first group include FWD (Falling Weight Deflectometer), GPRS (Ground Penetration Radar System), APL (Analaizateur du Profile en Long), SCRIM (Sideway Force Coefficient Routine Investigation Machine), SUMMS (survey Machine for Macrotexture and Skid), and Texture Meter. The methodologies of the second group are based on video cameras. The survey methodologies for geometric characteristics include the traditional optical instruments, GPS, aerophotogrammetry, and LIDAR, while the methodologies of the last group include the traditional optical instruments and Laser Scanner.

Some owners, such as Autostrade s.p.a. and ANAS, respectively the main motorway company and the national company for state roads, have a long tradition and deep and active experience in road maintenance and its quality control, while the introduction of C.S. has also awakened small owners and administrations. Recently we have witnessed in professional journals and magazines examples of the use, by technical staff of sensitive local administrations and related construction firms, of modern technologies (such as FEM, GPS, GPRS, FWD, etc.) to study the whole cycle of the renewing asphalt process, design, recycling, and the

quality control of work. Taking into consideration the methodologies of C.S. software for CAD, GIS, and imaging and also its recent practical introduction, we can conclude that the Onwers and construction firms are receptive to automation for road rehabilitation. The related methodologies are perhaps not common but "accepted" for the three stages shown in figures 3 and 4: a) initial data measurement; b) CAD design, analysis of measurements, product design, and modeling ways, etc.; and c) quality measurements.

Other methodologies, such as Automated Machine Control and Quality Documentation, Machine control Modeling, and typical computer integrated road construction technologies, now seem to be unknown objects or topics, ma we could be denied just tomorrow. That isn't a critical opinion, but a simple recognition made speaking with university researchers and teachers working on transportation and road construction. The technical staff of the road machines makers is aware of or knows these topics, in particular the machine control by GPS or 3D Laser Total Station, but they are less sensitive for the data exchange technology. Probably this lack of sensitivity depends on the market conditions.

4. FUTURE STEPS TOWARDS AUTOMATED ROAD REHABILITATION PROCESSES - CONCLUSION

In Italy all the national and local road data banks have opened and consolidated the use of information technologies and sensors/instrument systems in road management, but the entry of automation in the road maintenance depends on the level of the technological knowledge, technical skill and involvement of the Owners. Moreover some systems or methodologies to measure asphalt and road parameters haven't supported by national standards, so it's difficult to compare all the methods and values.
Really, in Italy we focus our attention on other problems that the IT in road maintenance allows to put in evidence. The high density and the heavy commercial and touristy traffic, the young and unstable geology of Italian territory make necessary the continuous maintenance of tunnels, viaducts, bridges and road paving with heavy impact on the traffic. So the mobile yards for road paving maintenance should be short, with short feedback in space and time for the quality control of processes and remotely managed. To integrate and automated the road machinery, to make short the yard, improve the on-line and on site control of processes quality could be a research activity in road rehabilitation automation.

In Finland many companies have already abilities to extensive initial data measurements and also smart rehabilitation design. However, in the total process of road rehabilitation this more accurate "smart" rehabilitation method is today not yet collectively understood. A rehabilitation design can also not yet be processed to machine control models to be utilized in the control of different work machines. That requires also more development activity. In future, the main benefits of automation will be attained through the total process of rehabilitation. All of the workers in different phases of road rehabilitation should develop automation together.

There are several advantages when automated road rehabilitation process is completely working. The rehabilitation structures can be optimized in both longitudinal and transverse section, which mean more uniform and sustainable rehabilitation solutions. The method allows also the design for shorter sections and also thickness can be changed more frequent. These can result major cost savings. Automated rehabilitation process allows also faster machinery work which reduces the time of closures and reduces the road users costs.

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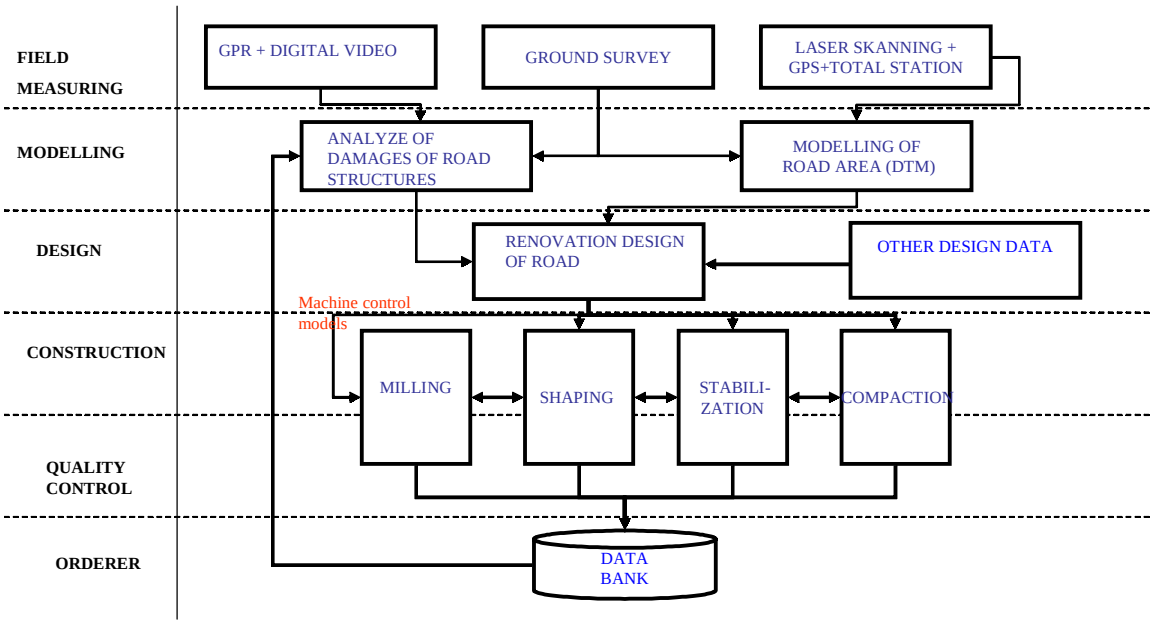

Figure 6. Process model of road rehabilitation - Finland.

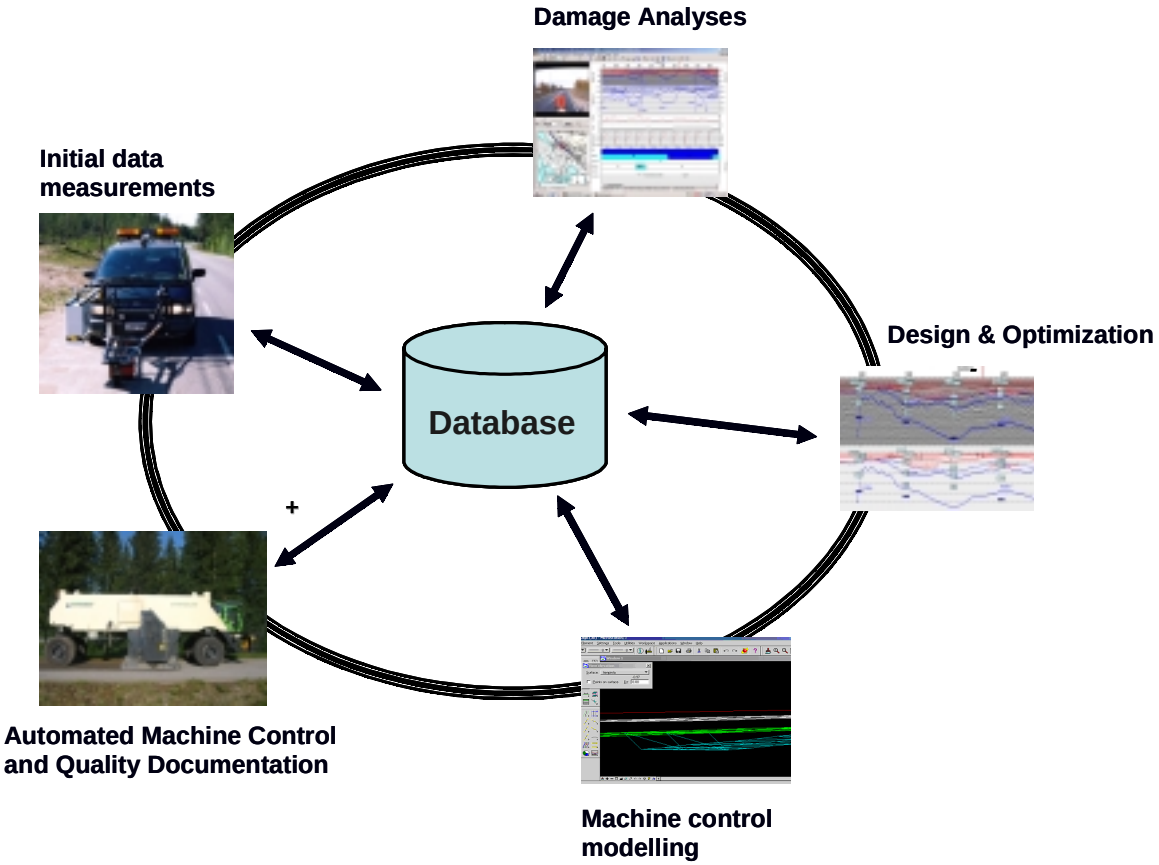

Figure 7. Total process of road rehabilitation - Finland.

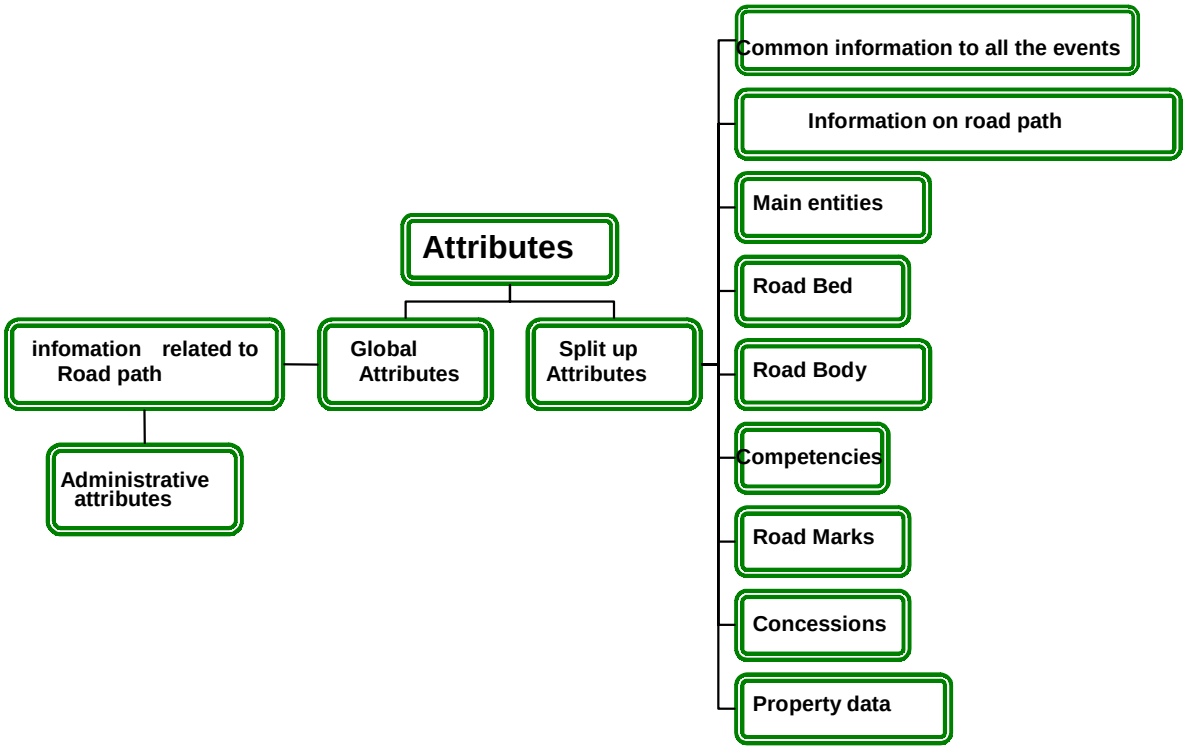

Figure 7. Global and Split up Attributes – Italy.

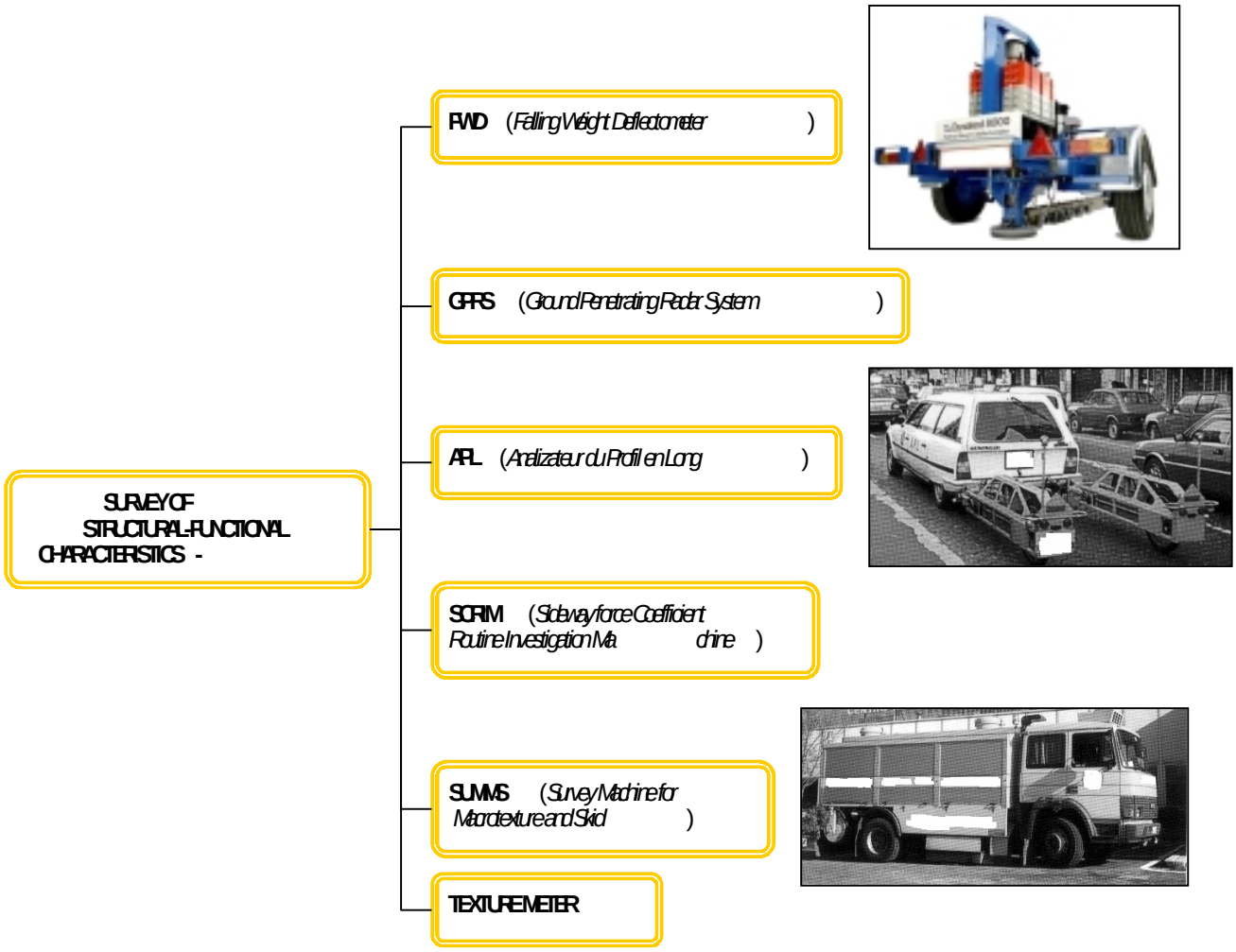

Figure 8. Methodologies for survey of the structural-functional characteristics – Italy.

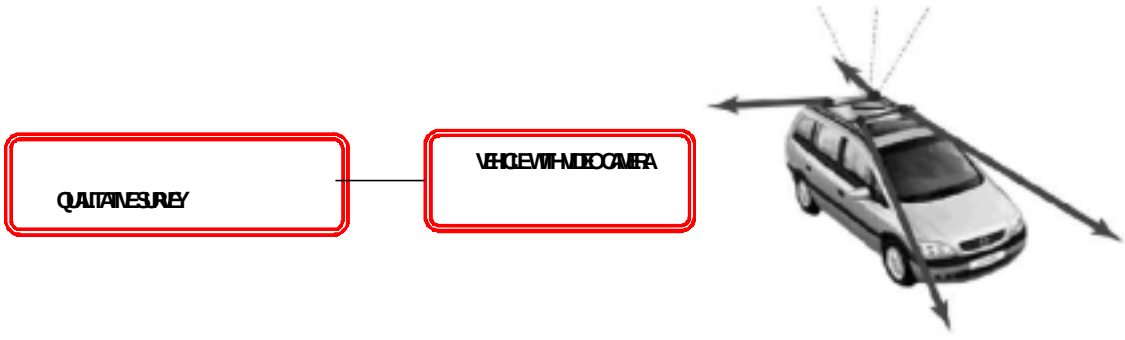

Figure 9. Methodologies for qualitative survey – Italy.

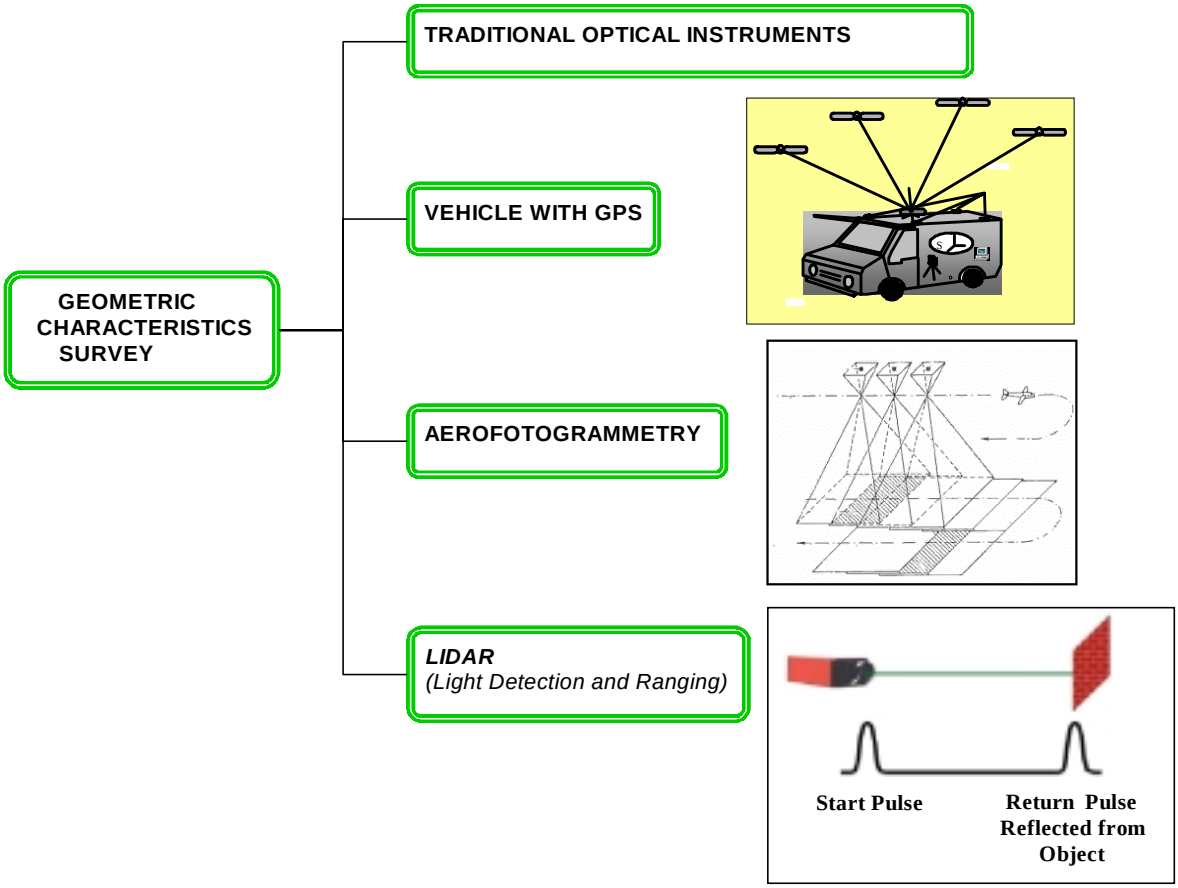

Figure 10. Methodologies for geometrical characteristics – Italy.

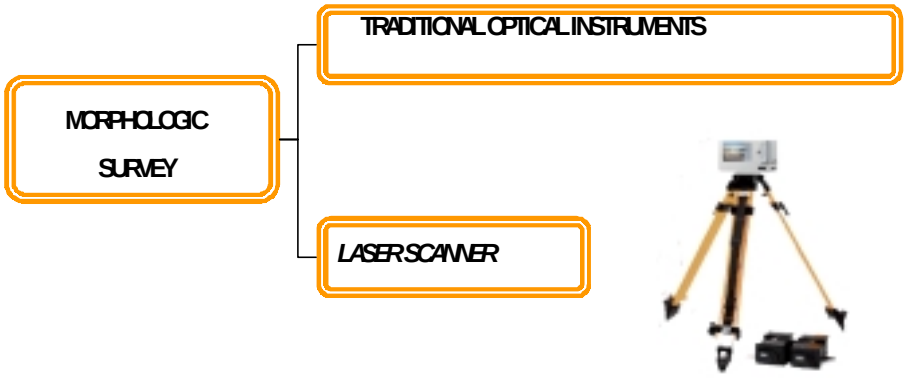

Figure 11. Methodologies for the morphologic survey – Italy.

ANALYSIS AND UTILIZATION OF QUALITY COST IN CONSTRUCTION PROJECTS

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Abstract:
In the customer-focused paradigm, high quality products or services can strengthen competitiveness, raise market-share, and provide a basis for long-term relationship with owners. But in most cases, the lack of quantitative data makes it difficult for managers to judge the current status of quality appropriately during a construction phase. Although quality is one of the critical success factors for evaluating a construction project, there is no practical guideline for measuring quality. As a solution to this problem, this study proposes a method to measure and analyze quality cost in construction projects. Quality cost plays an intermediate role in managing quality from a cost perspective and consequently contributes to the success of the construction project.

Keywords:
Quality, Quality Control, Quality Cost, Multi-Dimensional Analysis

1. INTRODUCTION

1.1 Background and purpose

Due to the diversification of customer needs and the emergence of multi-functional buildings in recent years, the tasks of construction companies have changed from being producer-centered to customer-centered. With this shift in the business environments, construction companies are pursuing continuous quality improvement to meet customer demand. They are putting great efforts to improving their quality by recognizing the limitations in the existing quality control mechanism which are mainly centered on performing inspection and test of finished work and restructuring process to prevent defects during the construction and operational phases.

Maintaining good quality is one of the main objectives of construction management in addition to meeting designated schedule and cost. In addition, quality is one of the important factors considered when determining the success of a project.[1][2] So most construction companies are now in search for a new method to achieve target quality at the most optimal time and cost.

In this study, we found a method with which effectiveness can be enhanced in terms of quality control and ultimately the overall construction management process. Here, we propose measuring and analyzing cost related to quality in construction phase of project. Executing quality control based on quantitative data is expected to contribute to achieving construction projects' various goals, that is, quality, schedule, and cost.

1.2 Scope and method

Quality in construction projects can be classified in various ways. There are various objects and methods of quality control according to phases of the project life cycle, and project participants tend to evaluate these results according to their own targets and criteria.

In this study, we have limited the research scope to the construction process where the physical product of construction work is made with resources. Here, we identified quantitatively measurable costs among the quality cost categories, comprising quality control cost and failure cost and then reviewed the method to measure and utilize those costs in quality control.

This study was executed as follows.

1) The overall quality and quality cost were examined.

2) The definition and measurement method for quality cost in a construction process was reviewed based on previous researches and cases.

3) The measurable quality cost items were selected and a method of collect such data was developed.

4) A new process of measuring quality cost based on existing quality control work process was re-established.

5) A method to analyze quality cost multi-dimensionally was developed.

6) A method to utilize analysis results in quality control and other construction management areas was considered.

2. LITERATURE REVIEW

2.1 Quality control in construction projects

Quality control in construction projects can be described as organized efforts in maintaining and improving quality of buildings to produce buildings on a more economic level. Quality is defined as "conformance to established requirements".[3] By avoiding dealing with the degree of goodness or satisfaction, this definition provides a basis for measurement, i.e. the requirements are either met or not met. This definition is well suited with the objective of identifying costs associated with quality problems.[4] Furthermore, it implies that understanding requirements thoroughly is important to proper quality management.

In general, quality is measured based on whether the expected levels of quality by the owner, design quality of the designer, and construction quality of the contractor on site are achieved. So in each phase, it is important to investigate these requirements by the executing parties.

Figure 1 shows a general quality control process in a construction phase. According to Figure 1, quality control task is executed along with work progress. If the finished work has no problem, quality control task is performed along the middle area of the Figure 1. But if defects are found, additional works described on the right side of the figure are carried out. If the qualities of resources and finished works conform to the specified standards, the results of the inspection and test will be stored for future reference in other projects.

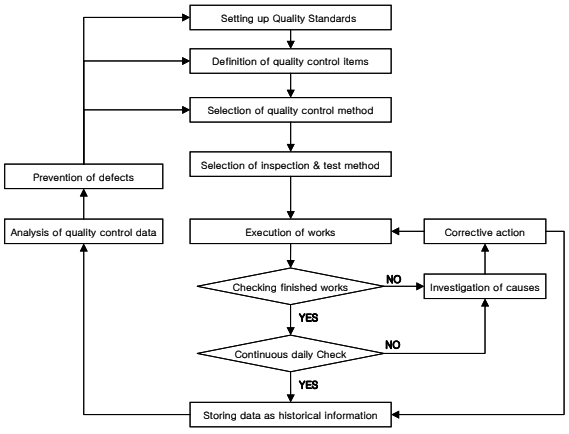

Figure 1. General Quality Control Process in Construction Phase

2.2 Quality costs

1) Concept and structure of quality costs

PMI(2000) defined cost of quality as all the efforts to acquire the quality of product and service, and these efforts include every work needed by requirements and rework.[5]

Quality costs can be classified as conformance costs and non-conformance costs(failure costs). Conformance costs are the costs for achieving satisfactory quality and non-conformance costs are the costs originated from low quality level. Table 1 shows the general classification and explanation of quality costs. Conformance costs include prevention costs and appraisal costs, and non-conformance costs are composed of internal-failure costs and external-failure costs.

Table 1. Classification of Quality Cost

Category		Contents
Conformance Quality	Prevention Cost	- Cost arising from prevention measures - Cost related to education, planning, etc.
	Appraisal Cost	- Cost related to performing check on products or services - Cost for conducting inspection, lab test, on-site test etc.
Non-conformance Quality	Internal-Failure Cost	- Cost related to resolving problems prior to delivery of product to customer - Cost related to disposal, re-production, stand-by etc.
	External-Failure Cost	- Cost related to solving customer claims in connection with products or services - Cost related to maintaining quality assurance, exchange, refund etc.

2) Quality costs and quality level

If quality cost means the whole cost spent to assure quality in corporation, quality costs are estimated up to 20 - 40% of its revenue.[6]

This concept of quality cost has been revised from the traditional perspective where prevention cost and appraisal cost offset failure cost(see figure 2-A) to the concept whereby achieving quality and cost reduction together is more important.(see figure 2-B)

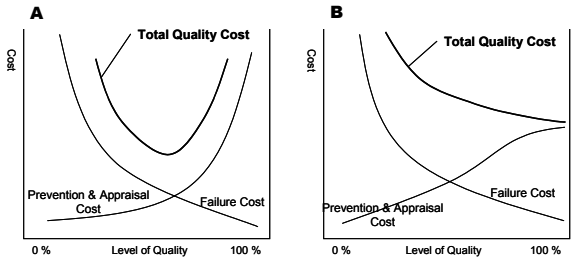

Figure 2. Relationship between Quality Cost and Quality Level

Quality manager should consider that increasing appraisal costs have no impact on the entire quality cost because internal-failure costs from rework or repair will still increase despite reduction in external-failure costs. So it is important that companies focus on cutting down failure costs by reinforcing prevention activities in the early stages.

2.3 Quality cost in construction projects

Quality control cost included in costs of construction projects is the costs required by related regulation and contract conditions for achieving quality of contractual object.

CII(1994) investigated 12 construction projects in U.S. and found quality control cost to be 8.1% of the entire contract sum[7], and PMI(1991) presumed that quality control cost was approximately 3-5% of entire project cost.

2.4 Related researches and cases

1) Researches on quality cost in construction

Davis(1989) classified the quality costs as the costs for quality control that comprise of prevention cost and appraisal cost and the costs for actions taken for deviation.[8] And Davis measured cost from quality control activities and rework by collecting labor working hours. He found that quality-related works took up 47.2% of all the design-related works. This study, however, appeared to have some vagueness in criteria by which 15 quality control activities and 24 rework-related tasks were selected, but showed that resources and costs required for quality control are not negligible

Burati(1992) traced causes of deviations and measured the cost incurred for correcting them.[4] In his study, Burati categorized causes of deviations into 5 areas: design, construction, fabrication, transportation, and operability, and each area had 3 types of deviation: change, error, and omission. Based on the data from 9 construction projects, Burati concluded that costs from deviation at the design phase and construction phase took up to 9.5% and 2.5% of the whole cost respectively. This study had its own significance in estimating internal-failure cost, but also showed limitations in its analysis in that it only defined data in the past.

Ledbetter(1994), who suggested Quality Performance Management System(QPMS) with Burati in CII, measured costs from quality control activities and rework.[7] The drawback was that QPMS could only be applied for estimating labor cost. With the framework of QPMS, Ledbetter analyzed data from 12 construction projects and found that labor-related quality cost was up to 11.2% of entire labor cost.

Love(2003) developed Project Management Quality Cost System (PROMQACS).[9] PROMQACS was constructed based on standard quality cost structure, and is useful in accumulating related data and sharing them with participants. But there exists no specific method for collecting quality-related data on construction projects. Also, his study did not provide detailed explanation about the relationship among quality, schedule, and cost though PROMQACS estimated the impact on schedule and cost.

The previous researches on quality control and quality cost in construction projects have demonstrated that there has been few effort to accurately measure quality cost incurred in the design and construction phases. In fact, most of these researches were focused on tracing the causes of defects and estimating cost from corrective actions based on data of the past.

2) Case study on quality cost in construction

Company A has a category of quality-environment management cost in control budget. Table 2 shows the relevant items taken into account in quality control in that category. Prevention cost and appraisal cost are seen to have been included as indirect cost, but failure costs are not included.

Table 2. Cost for Quality Control

Category	Items
Quality Control Direct Cost	Curing / Line -setup Material cost / Waterproof test Lightings in basement
Quality Operation Cost	Testing lab Test equipment / Cost for test
Quality Control Labor Cost	Tester Labor cost
Quality Control Material Cost	Material reserved (tiles, floor materials, windows, hardware etc.)
Others	Regular test / Project record Print Survey / Other Design cost

Company B uses a Quality Cost Estimation System and has its own quality cost structure as illustrated in Figure 3.

Quality cost data from each project are collected through the internet based on quality cost structure.

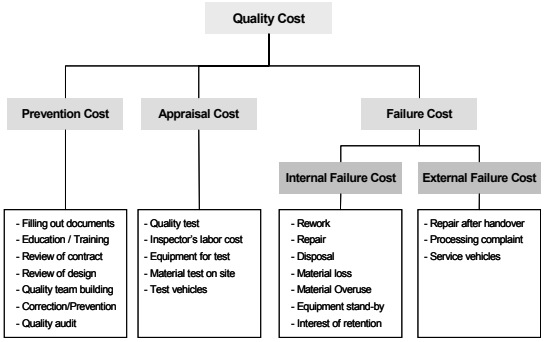

Figure 3. Classification of Quality Cost (Example of Company B)

By using the Quality Cost Estimation System, a quality manager can judge the status and time-series trend of quality cost. Figure 4 shows a user interface of quality cost status on project level.

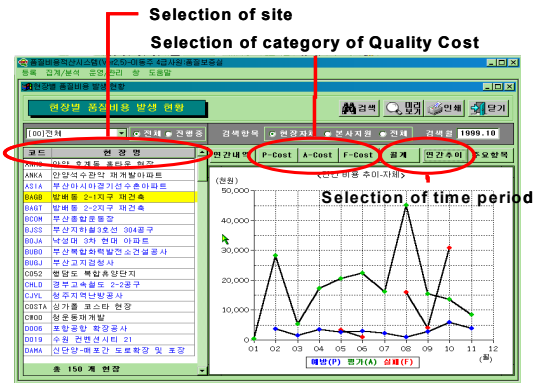

Figure 4. Example of Quality Cost System

2.5 Measuring quality cost

As the scope of quality cost has expanded, it has become more difficult to obtain an accurate measurement and evaluation of quality cost. In many cases, it is difficult to quantify quality cost and to separate it from indirect cost or fixed charge.

To collect related data and estimate quality cost accurately, it will be necessary to set up and operate a quality control process, especially process of inspection and tests.

Costs incurred in connection with quality managers at the head offices and sites and workers can hardly be estimated. The fact that companies tend to avoid revealing failure cost is also an obstacle in data collection.

3. METHOD FOR MEASURING AND ANALYZING QUALITY COST

3.1 Selection of quality cost items

Definition and scope of quality cost are different for each literature and author, and in some cases companies have specific quality cost items that is considered internally. These factors should be taken into account when selecting quality cost items in construction projects. In addition, items should have objectivity in order to use them in the public sector.

And items should have standardized structure to prevent confusion because the structure of quality cost will influence the aggregation in analysis process and the connection with schedule and cost data.

Normally quality control costs composed of prevention cost and appraisal cost are included in project budget as required by the relevant regulation and can be estimated with the processed data from the site. And data related to external-failure cost are collected through the various computer programs supporting the maintenance and operational activities. Thus, in this study, we focused on the measurement and analysis of internal-failure cost incurred from rework.

3.2 Method to measure quality cost

In case of manufacturing industry, most of the data related to quality cost were gathered from the accounting data. And the quality costs were estimated by product or by production line in accordance with the predetermined criteria.

Quality cost incurred from rework in construction was estimated by various ways from additional direct cost such as cost related to labor, material, and equipment to indirect impact on project such as schedule delay or cost overruns. This study considered the method below for substantial measurement of internal-failure cost during construction phase.

Field engineers inspect finished work and measure the quantity of rework if required on site. Rework cost is estimated through mathematical operation of measured rework quantity and unit cost below.

Internal-failure quality cost unit price
= Demolition unit price + Disposal unit price + Rework unit price

Demolition unit price is determined by cost from labors and equipment required for removal of defective finished work. Disposal unit price, if deemed required, is estimated based on the actual expense. Unit price specified in the control budget or contract document is applied as the rework unit price. Measurement of rework cost basically follows the process shown in part of Figure 1.

3.3 Analysis of quality cost

Managers in charge of performing construction site check status and direction of quality control activities by analyzing measured quality cost from various viewpoints. In addition, they refer to those results in making decisions for other construction management areas such as schedule and cost management. This study employed the concept of multi-dimensional analysis. Figure 5 shows an example of dimensions in analyzing quality cost. All the dimensions are designed to have a hierarchy and quality cost data can be aggregated according to this hierarchy. The structure of dimensions is utilized in creating cubes in multi-dimensional analysis and when using other analysis tools.

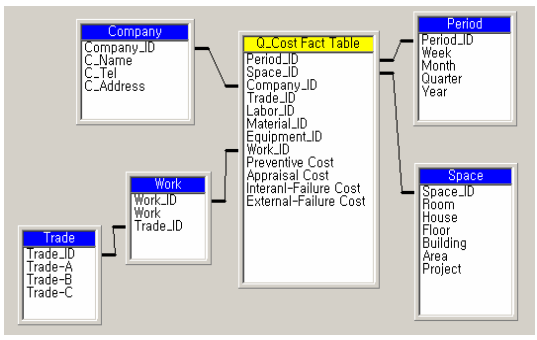

Figure 5. Schema for Quality Cost Analysis

And quality cost can be analyzed through other methods such as comparative analysis, trend analysis, and composition analysis described below.

1) Comparative analysis

Comparative analysis is performed to judge the quality level of a project by comparing quality costs against specified dimensions. Figure 6 shows the analysis of quality costs by periods and areas with pivot table function provided by Microsoft Office Excel.

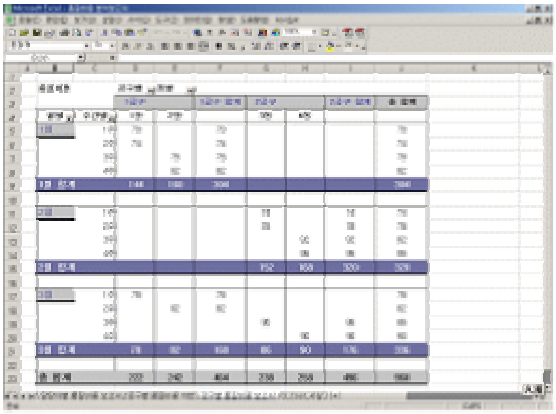

Figure 6. Analysis by Time and Areas

2) Trend analysis

Trend analysis is a method to evaluate current level of quality control activities by analyzing the trend of quality costs by time periods.

3) Composition analysis

Composition analysis is performed for analyzing the changes in proportions of each quality cost item. When applying this method, managers check the proportion of each item along with the changes of the overall quality cost.

3.4 Connecting Quality cost with schedule and cost

Quality cost is used as indicator to evaluate quality performance and influences companies' financial performance. To achieve the goal of quality control in construction project, not only quality but also other factors affecting project success such as schedule, cost, safety should be taken into consideration at the same time. Because quality cost during construction phase can have an effect on schedule and cost, the degree of influence should be reflected on the overall project cost and schedule at the planning stage.

3.5 Utilization of analysis results

Expected utilization of analysis results suggested in this study is as below.

1) Sub-contractor management

By providing rework cost and causes of defects, quality cost data can contribute to effective sub-contractor management. Quantitative information on the cost incurred in maintaining proper quality will enable managers to recognize the importance of quality control activities, to reinforce work control on site, and consequently to enhance overall quality level of the project. On the other hand, managers refer to historical quality cost data of the sub-contractors in selecting a specific sub-contractor for a certain project because high quality cost implies potential risk in labor control and finance.

2) Reinforcement of preventive activities

Quantification of quality control activities and analysis on causes of rework can contribute to the reduction of comprehensive cost by reinforcing preventive activities in future construction. Causes of rework can be reflected on quality plan, ITPs (inspection and test plans), and checklists. These information will be more valuable when only limited resources can be allocated in preventive activities on site.

3) Connection of quality with schedule and cost

By using schedule data and cost data in analyzing quality-related data, all the management areas are connected systematically, based on which a new management information can be derived.

4) Determining priority in quality improvement

As Crosby(1979) pointed out, measuring quality cost can help identify more benefit areas in cost through quality improvement.[6]

5) Feedback to design phase

By using non-conformance information from quality cost analysis in design phase, designers avoid works frequently causing defects.

4. CONCLUSION

Measurement of quality cost is important as a supporting tool to decide when, where and how to allocate resources on site. In general, quality issues are of less concern than meeting time schedule or cost requirements. In this study, a new method for achieving good quality control in terms of cost is suggested and ways to measure and analyze quality cost during construction phase were discussed.

Practically most of the cost and responsibility of rework are ascribed to sub-contractors, and so there is no additional burden on the contractors for handling quality-related problems. But it is important that all the participants pay more attention to non-conformance situations because they cause many secondary problems such as schedule delay, cost overruns, sub-contractor insolvency etc..

In the future, a physical system based on the concept suggested in this study will be developed, complimented by qualitative factors on quality.

Acknowledgments

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Application of Engineering Management Information on Construction Disputes and Claims

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ABSTRACT: The high risk, uncertainty and complicated interface for division of work in the construction industry have resulted in endless engineering dispute issues. Submitting claims during the performance of construction contracts can be money wasting and time-consuming process. This paper summarizes dispute issues occur often on construction site, clarifies what responsibility each party should bear, identifies the compensable claim items in each dispute issue and lists suggestion estimation formulas for each claim item for quantifying. By using eEPC diagram to represent management process in General Construction Company (GC), the paper pioneers in discussing the proof evidence required by each construction claim and mapping among daily management records. According to the mapping, construction managers can efficiently clear up daily management records they need for testifying truth and calculating compensation amount. Finally, the study adopts object-oriented technique to develop a Construction Claim Decision Making System (CCDMS) for implementation. CCDMS displays entitlement and claims quantum for assisting claim presentation.

KEYWORDS: Construction Disputes and Claims, Daily Records, Construction Claim Decision Making System (CCDMS)

1. INTRODUCTION

Since construction itself is a complicated, high risk and uncertain task, it is hard for constructors to identify their claim item and compensation amount, when a construction dispute arises unexpectedly. If the compensation items and amount could be known as early as possible to serve as reference for decision-making whether a claim is to be raised or not, the constructors would probably save their loss in today's vacillation business environment.

This paper summarizes dispute issues often occur in construction contracts, making clear what responsibility each party should bear, identifying the claim items for each dispute and listing suggested quantitative formulas for each claim item to assist project manager in construction claim process. In this way, constructors can not only detect claim item "timely" and "accurately", yet still effectively make a decision whether to raise a claim or not.

In this research intends to collect and clarify correlation between claim item and corresponding evidence records in management activity. When a construction claim arises, constructors are able to submit correlated documentary evidence from management process. This can prevent constructor from losing his due rights because of shortage or impropriety in the evidence records.

In this research, a Construction Claim Decision Making System (CCDMS) is developed to automate the claim process and calculate the claim quantum amount. It sets a step-by-step procedure for collect and clarify dispute causes occurred in construction contract and find out the items that can be claimed for compensation according to a variety of causes. Furthermore, it arranges relevant documentary evidence required by all kinds of claim items and provides the pilot calculation function for the compensation amount so that the constructor can correctly identify the claim item, collect hard facts and estimate time extension amount and cost recovery for compensation. Provided to the constructor, this system serves as suitable analysis and facilitating presentation during the course of a claim for compensation. This system is developed by object-oriented (OO) technique, which can help extensibility and maintainability of the system be fulfilled.

2. ESTABLISH CLAIM PROCEDURE MODEL

Some construction claims of excellent merit are lost solely due to failure of identifying them (Easton 1989). Hence, a step-by-step procedure will discuss dispute issues often arise in construction project, correspondence between dispute issues and claim item, and summary of proper quantitative formula for each claim item.

Summarization of Dispute Issues

Construction claims originate from a variety of causes both directly and indirectly (Stokes 1977). A number of major disputes can be largely traced to four basic types by responsibility. 1. Due to contractors (can be due to the first party), 2. Due to force majeure (cannot be due to either of the two parties), 3. Due to the causes created by owners (can be due to the second party) and 4. Due to the causes created together by owners and contractors (can be

due to both the two parties).

According to the above four types of liability. *Figure 1* presents dispute issues usually occur in construction work. There are 17(A1~A17) issues belong to the first party and 5 (B1~B5) issues which don't belong to the first party or the second party. Moreover, two compensation targets, financial claim or claim for extension of time (EOT) in each dispute issue is listed in the figure.

Take the A1 "Cannot Provide Area on Schedule" as an example, if this dispute issue arises, constructors can notify to owners to compensate for both financial claims and those for EOT. The purpose of making clear the Compensation Target is to make constructors determine efficiently which kind of claim should be submitted and provide right direction for further claim examination and documentation.

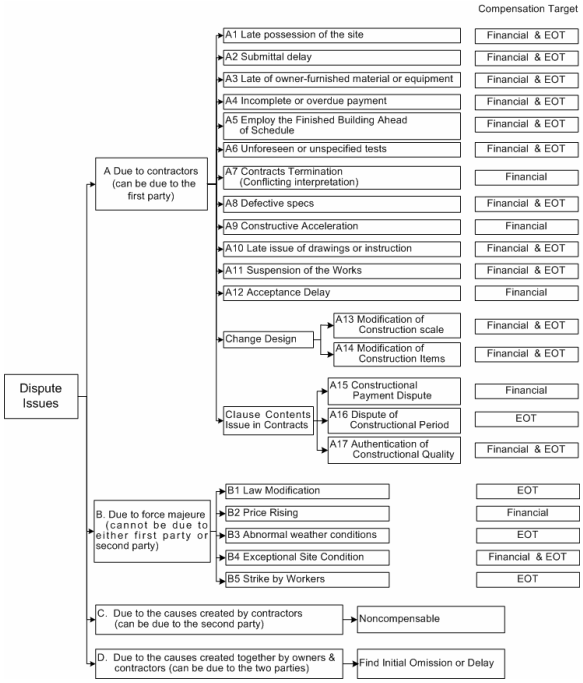

Figure 1 Classification of Dispute Issues & Compensation Target

Correspondence between Claim Item & Dispute Issues

In general conditions of the construction contract. The claim item generally proposed by the constructor fall under two major categories: cost and time. In the first category, the constructor asks for reimbursement to cover the following item C1~C20 shown in the *Table 1*. In the second category, the constructor requests a modification of contract delivery dates and milestones to offset the delays either caused by abnormal weather conditions or strikes (C21, C22) or not. If the require delay is not yet obvious, the common quantification analysis methods of CPM Techniques, Productivity-Loss estimation methods and Simulation techniques are usually used for delay estimation. The outcome of analysis is claim item of time extension (C23). (Jervis and Levin 1988) (AbouRizk and Dozzi 1993)

Table 1 Table of Possible Claim Item

No.	Claim Items
C1	Increased labor costs due to the quantity increasing (direct)
C2	Increased labor costs due to productivity-loss (indirect)
C3	Increased labor costs due to delay (direct)
C4	Increased material cost due to quantity increase
C5	Increased material cost due to unit price raising
C6	Increased cost due to added new portion of the work
C7	Increased cost due to newly added subcontract
C8	Increased overhead cost of equipment lease fee
C9	Increased overhead cost of equipment operation fee
C10	Increased overhead cost of site infrastructure
C11	Increased home-office overhead
C12	Increased insurance premium
C13	Interest of overdraft loans
C14	Profit lost during delay period
C15	Expenses of employing consultants
C16	Traffic control and security measures
C17	Labor Safety and Hygiene Fee
C18	Interest of Bond/Reserved Fund
C19	Construction cost of the item
C20	Renewal expense for building damaging, finished
C21	Delaying time cause by abnormal weather conditions
C22	Delaying time cause by strike of worker
C23	Extension of contract time

Note that the two categories are very much interrelated. For instance, any delays are apt to cause an increase in all cost items, and any productivity drop causes an increase in the duration required to finish the work. Hence, the contractor may claim any combination of the above factors, or possibly all of them. Therefore, study first divided compensation items into two classes: (1). Claim items which should be listed, (2). Claim items which are listed according to instances. To take the claim item related to dispute issue item about A1"Late possession of the site" as an example, its claim items that should be listed like C11 Increased home-office overhead, C13 Interest of overdraft loans, C14 Inflation cost during delay period and C23 extension of time. In addition, the claim items, which are listed according to instances, contain C8 equipment lease fee, C12 increased insurance premium, C15 expenses of employing consultants, C16 traffic control and security measures and C17 labor safety and hygiene fee. According to the above method of classification, each dispute issue is arranged and listed to correspond to every claim item as shown in *Table 2*.

Selection of Quantitative Formulas

If the analysis shows that constructors have valid grounds for a claim, the engineer now has the task of quantifying the amount of compensation (in term of cost and time) that the contractor is entitled to.

Table 2 Relation between Claim Items and Dispute Issues (Simplified)

		Code of Claim Items																						
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
Code Of Dispute Issues	A1								○			◎	○	◎	◎	○	○	○						◎
	A2								○			◎	○	◎	◎	○	○	○						◎
	….	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
	B1			◎								◎	○	◎	◎			○						◎
	B2			◎		◎						◎			◎									
	….	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…

◎ : Claim items that should be listed,
○ : Claim items that should be listed according to the actual circumstances

Table 3 Construction Claim Item and Evaluation Formula (Simplify)

No.	Claim Item	Evaluation
C1	Increased labor costs due to the quantity increasing (direct)	1. {[(Labor Cost under Quantity increase Condition－Labor Cost at Normal Condition)×(1+ Administrative Expenses)]}×(1+Profit) 2.Real Expense
…..	…….	…….
C23	Extension of contract time	1. Date of Delay

To achieve this proposal, the engineer has to resort to the very same quantification methods proposed earlier for use by contractor to substantiate the claim. *Table 3* is the outcome of selected common estimated formulas to calculate compensation amount about cost recovery. In *Table 3*, C23"Extension of contract time", delay analysis has a lot of complex quantification methods, for instance, CPM techniques, Productivity-Loss analysis and Simulation techniques etc. Contractor can select an advantageous method to demonstrate legitimate of the claim. Therefore, estimation of EOT is not included in this research. C1~C19 are the items about financial claim. There is no clear-cut method to quantify the cost damage in each item. Hence, based on the literature and domestic construction claim case review. This study lists most common acceptance estimation formulas to calculate the amount of each compensation item. As a result, *Table 3* serves as reference for constructor to quickly achieve the estimation formulas and provides a base for system to calculate the amount of compensation.

3. VERIFY EVIDENCE FOR CLAIMS

The contents of this stage will be divided into three parts for discussion. Firstly, by virtue of the representation of the GC's management process to make clear activity in each process and the records presented by various kinds of activities. Secondly, arrangement records can be used for calculating the damage or evidences for seeking compensation. Finally, with the help of case documents and interviews with practitioners, study confirms the correlation between the claim item and supporting records. Consequently, The main framework of this concept is demonstrated in *Figure 2***.** This concept is based on the claim items occurred by the dispute issue, constructors can easily, promptly and correctly know what records are required for each compensation claim items and which activity creates these forms in the management process of GC. Therefore, this will improve the efficiency and effectiveness for claim documentation; daily records also serve as reminders to engineers to avoid claims.

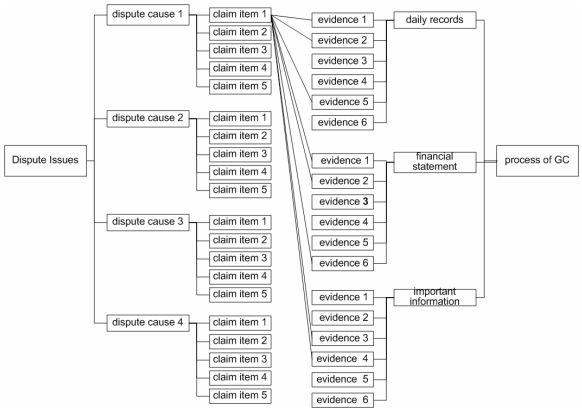

Figure 2 Relations Between Claim Items and Evidence in Process

Representation of Constructors Operation Process

Study has investigated the existing operation process of General Construction Company, established the management process of GC with the technique of process representation, and restarted the process with the help of the Event Guide Program Chain (eEPC) diagram in Architecture of Integrated Information Systems (ARIS) tool (Scheer 1994). The output, export documents requirement for every function activity, the department and personnel participating in execution of the flow are clearly described.

In this research, the Value-added Chain Diagram (VAD) is applied to divide the work and service operation of GC into 12 key management process (shown in *Figure 3*), clarifying each operation process of constructors, this study unfolds the detailed operation approach of every operation flow by means of the eEPC diagram. It uses the procurement/subcontracting process as an example for explanation (shown in *Figure 4*).

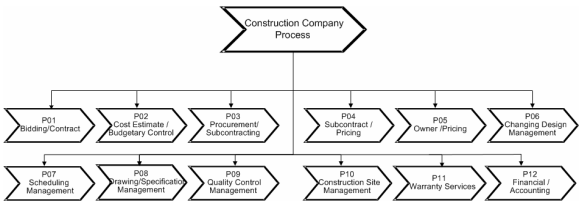

Figure 3 GC's main process by VAD diagram

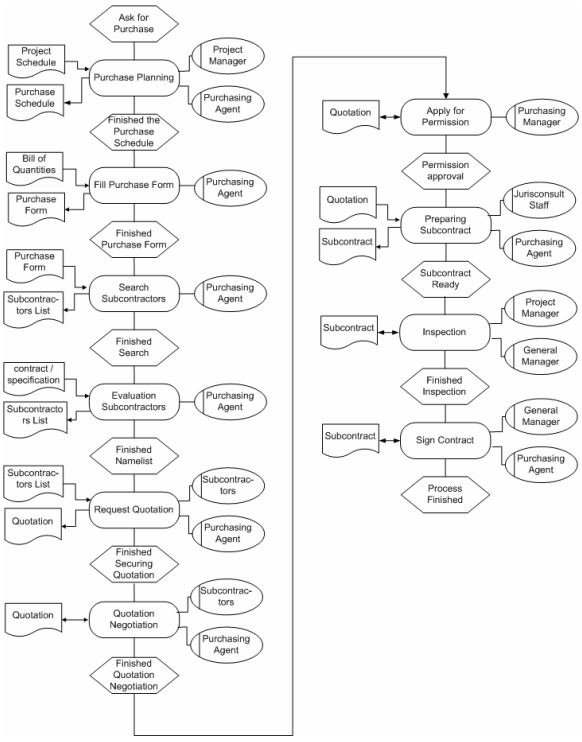

Figure 4 procurement/subcontracting process eEPC diagram

Arrangement Business Records for Evidence

After representation of GC's 12 processes using eEPC diagram, the study can clearly identify every input/output business records in each activity. Take the P03 procurement/ subcontracting process as an example, every business records export in each activity in procurement/subcontracting process are listed in *Table 4*. Each export document gives an identify number, for example, P03 means number 3 management process of procurement/ subcontracting, the rest two letters refer to activity in the process.

Based on this sequence for analyzing 12 processes in GC, study lists 120 records in management process which assign the start number of "P", 16 financial statements which assign the start number of "AC" and 5 important report assign the start number of "I."

Therefore, according to the precedent of domestic construction claim cases (Su 1997). Study has selected 28 daily records (listed in *Table 5*) from 141 documents represented in previous stage, which can be proved evidence used in claim analysis and documentation.

Table 4 Export documents in P03 procurement/subcontracting process (Simplify)

P03 procurement/subcontracting process		
No.	Activity	Export documents
P0301	Purchase Planning	Purchase Schedule
P0302	Fill Purchase Form	Purchase Form
……	……	……
P0310	Sign Contract	Subcontract

Relation Between Claim Item and Evidences

Documents are essential parts of effecting a successful resolution and disposition of claims. Each claim item needs its own daily records for claim analysis and documentation. Study has divided the evidences into two groups. Firstly, documents to prove the truth, which is the evidence to prove the claim event actually occur or exist. In those documents, claim representatives can identify conflicts between project and contract; it can recognize the dispute arising time, description about claim item. Secondly, the documents can provide the time and cost elements to assist in calculating loss. Base on the claim item listed in *Table 1* and the evidences selected in *Table 5*. *Table 6* is the result of correspondent between claim item and evidences, which is accumulated in this study. For instances, if claim item C1 "Increased labor costs due to the quantity increasing (direct)" is needed for compensation. Claim representative can easily refer table 6 to identify records needed for submitting this claim item, it needs to collect P0103 Project correspondence, P0604 Written variation order, P1002 Progress photo with commentary, P1003 Minute of site meeting, P1008 Daily work & progress reports for truth proven, and P0203 Bill of quantities document, P0305 Quotations, P1005 Site diaries, AC1 Crew hours summary/Payroll records to calculating compensation amount.

Table 5. Evidences for claim documentation

No.	Support document
P0103	Project correspondence
P0105	Condition of contract & specification
P0203	Bill of quantities document
P0208	Productivity & cost reports
P0305	Quotations
P0310	Subcontract & specification
P0407	Payment application & certificates
P0503	Delivery records
P0604	Written variation order
P0705	Construction schedules

P0802	Drawing register
P0903	Records of inspections & directions
P0907	Register of Submittals
P0909	Accident & site safety reports
P1002	Progress photo with commentary
P1003	Minute of site meeting
P1005	Site diaries
P1007	Records of delay & disturbance
P1008	Daily work & progress reports
AC1	Crew hours summary/Payroll records
AC2	Payment receipts
AC3	Journals/ledgers
AC4	Interest expenses (bond, fund, etc)
AC5	Interest loss (delay parments, etc)
AC6	Field office expense docket
I1	Important news (strike, price-hike, etc.)
I2	Economic policy report
I3	Ten years domestic weather records

Table 6 Relation between claim item and evidences (Simplify)

	C1	C2	C3	C4	C5	C6	C7	C8	…	C22	C23
P0103	◎			◎		◎			…	◎	◎
P0105					◎				…		
P0203	○	○	◎	○	◎	○		○	…		
P0208		○			○				…	◎	
P0305					○	○	○		…		
P0310							◎		…		
P0407					◎			○	…		
P0503				◎	◎				…		
P0604	◎			◎		◎			…		
P0705		◎	◎						…	◎	◎
P0802	◎			◎		◎			…		
P0903		◎				◎			…		
P0907									…		
P0909									…		
P1002		◎						◎	…		
P1003						◎	◎		…	◎	◎
P1005	◎	◎	◎	◎	◎	◎		◎	…	◎	◎
P1007			○					○	…	○	○
P1008	◎	◎		◎		◎		◎	…		
AC1	○	○	○			○	○		…		○
AC2							◎	◎	…		
AC3	◎				◎				…		
AC4									…		
AC5									…		
AC6									…		
I1									…	◎	◎
I2									…	◎	◎
I3									…		

◎：records to prove the truth
○：records to calculate compensation amount

4. Develop Construction Claim Decision-Making System

In order to automate claim examination and documentation, this research integrates the step-by-step process established in previous stage. Conduct with object-oriented (OO) technique to develop a Construction Claim Decision Making System (CCDMS).

System Analysis and Design

In the purpose of the analysis and design phase, study has adopted UML to identify user requirements, system operation and system architectural. The essential use case diagram of the system is shown in *Figure 5*. This diagram presents a dialogue between the actor and the system. The three-tier architecture system is established. In the application logic layer, which includes User management module, Case management module and Claim process module.

System Demonstration

Take Claim process module as an example, the operation steps are described as follow:

(*1*).*Create a new claim case and select dispute issues*

Users are able to create a new claim case name and select dispute issues due to owners or force majeure happen in the case; system provides "Case Inquiry" bottom to provide users refer other simulate cases for dispute issues selection.

(*2*).*Input EOT and select claim item*

Based on dispute causes of which users are selected, system automatically displays the suggestion list of claim items including items which should be listed and items listed according to actual circumstances.

(*3*).*Calculation of Claim quantum*

System shows estimate formula of each claim item according to claim item user has been chosen. Also, system provides "Evidence Inquiry" bottom. It can list the daily records that user can inquire numerical data to assist damages calculation, to prove the truth and related management process.

(*4*).*Print Result*

System display suggests compensation result show in *Figure 6*. The result includes claim case name, dispute causes, total amount of compensation and extension of contract time.

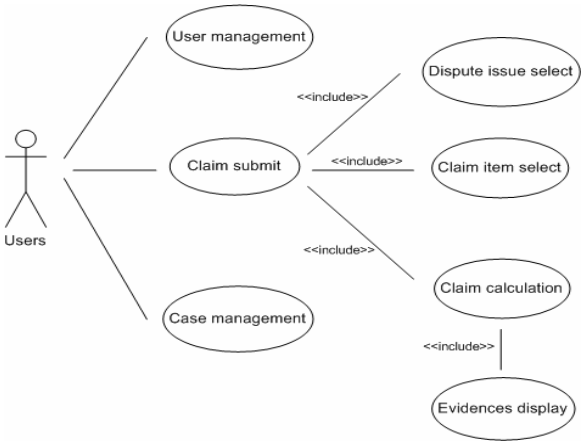

Figure 5 System use case diagram

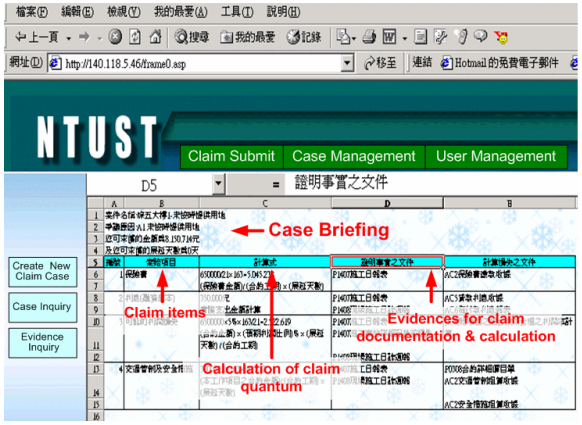

Figure 6 Suggests compensation result

5. CONCLUSION

This research can be concluded as follows:

Summarization of dispute issues

Construction claim identification involves "timely" and "accurate" detection of a construction claim. Some construction claims of excellent merit are lost solely due to failure of identifying them. Thus, study summarizes most common dispute issues occur in the construction contract, provides construction manager or engineer not only prevents potential construction claims, but also avoids dispute issues on the construction site.

Correspondence between claim item and dispute issues

Study examines correspondence between claim item and dispute issues. It helps construction manager or engineer select common remedies for claim based on dispute issues. It also lists claim items according to the actual circumstances. Claim participants can examine the actually condition on site and chose possible claim item without missing compensation rights.

Relation between claim item and management Process/ records

Study uses eEPC diagram to represent the records in every GC's management process. Collect management records can be used for evidence, including records to prove truths and records to calculate the damages. This is useful not only in collecting evidence during claim documentation stage, but also reminding engineers to pay attention to certain records of which process should be carefully recorded and preserved in daily management.

Construction Claim Decision Making System

Study adopts object-oriented technique to develop a CCDMS. System displays the entitlement and quantum for assisting claim presentation. In addition, system is composed by reusable object; therefore, user can modify system without changing the entire system.

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VALUATION AND COMPUTING ALGORITHM FOR BOT ASSOCIATED BUSINESS

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It is not unusual that BOT firms are granted to develop or operate certain business/project beyond the main scope of a BOT project, such as the surrounding land development. By granting these BOT project associated business, government can improve the project expected return and financial viability, and encourage potential developers to participate in BOT projects. Nevertheless, for host government, it is very difficult and subjective to evaluate the motivating effects or policy effectiveness. For developers, inaccurate valuation of associated businesses may cause serious bias during BOT project bidding process. For fund providers, such as lenders, contract design depends on accurately evaluating the overall value and risk level of a BOT project. As a result, it is crucial to accurately price the associated business. In this paper, real options theory, a dynamic asset pricing approach, is used to evaluate the associated business. Theory of mechanism design based on game theory is incorporated with the real options to investigate the government policy effectiveness and optimal policy design. A computing algorithm for valuation and optimal debt contract is developed.

Keywords: BOT、Mechanism Design、Real Option Theory

1 INTRODUCTION

It is not unusually that BOT firms are granted to develop or operate certain business/project beyond the main scope of a BOT project, such as the surrounding land development. This type of privilege typically exists when the project itself is not able to pay off the project cost and cannot create a sufficient amount of profit to compensate for the risks involved. These secondary businesses will be termed Associated Businesses in this paper. By granting associated business, government can improve the project expected return and financial viability, and encourage potential developers to participate in BOT projects. As a result, the associated business can be considered as the subsidy to the project, and therefore, the value of the associated business were it traded in the market is a cost to the government. In the paper, the cost is called the “policy cost.” However, the value of the associated business is not necessarily the same as its market value due to the common practice of restricting the promoter’s right of trading their equity shares the BOT project. The value distortion on an asset due to such restriction is discussed by Ingersoll (2002). As a result, the effectiveness of the granted associated business should be judged by how valuable the associated business is to the BOT project promoters. For host government, it is very difficult to evaluate the policy effectiveness.

The information asymmetry problem for fund providers is another difficult issue in BOT. The associated business is often distinctly different from the main scope of a BOT project in many perspectives, such as risk characteristics and management/developing flexibilities. For example, the developer often has options to decide the type or risk level of the associated business. Fund providers cannot observe or learn ex ante what risk level the promoter will choose for the associated business. In other words, the risk level information is private to the project promoter. As a result, it is important for fund providers to design different contracts that can have the promoter self-select into different type of contract according to their own private information, i.e., their intention for the risk level of the associated business.

Since the associate land development is one of the most often granted associated businesses in BOT, this study focuses on the land development rights. In this paper, modern financial theory and game theory are used to price the associated business, and furthermore to develop a model to examine the policy effectiveness and to design loan contracts. Theory of mechanism design based on game theory is incorporated with the real options to investigate the government policy effectiveness and optimal debt contract design.

We will introduce the methodologies used for model development in section 2. In section 3, we will, discuss the quantitative model for analyzing the

subjective value and market value of the associated business. Lastly, we will give our suggests regarding the mechanism design of a BOT project.

2. LITERATURE REVIEW

To enhance a BOT project's financial viability, the associated business, a subsidy from such perspective, could be considered as a motivating policy toward a specific project set by the government (Chen, [3]). Chen [3] apply game theory to analyze the concessionaire's investing behavior. Current research in finance has been discussing the efficiency and valuation of the motivation effectiveness of the 'manager's compensation' (Lambert, Larcker, and Verrecchia, [11]; Carpenter, [2]; Ingersoll, [10]). This line of research focuses on the asset value distortion due to the restriction on the manger's own investment portfolio.

Option pricing theory was developed by Merton [14] and Black-Scholes [1] in 1973 and researchers made considerable progress recently in valuation and application of nontraditional options. The valuation model we used to evaluate the associated business of a BOT project is called 'barrier option pricing model,' discussed by Ingersoll [8, [9], and [10]. The fundamental assumptions beneath of this model make it more applicable to our research than other models. The main reason is that Ingersoll's model is built on the assumption of "utility maximization" as discussed by Merton [13], and deals with the problem under the situation of "liquidity restraint," which means the decision-maker is forced to maintain a certain proportion of his total assets on a certain kind of risky asset. Lambert, Larcker, and Verrecchia [11] also build their valuation model on the basis of "utility maximization" principle. In their model, they limit the randomness of decision-maker's portfolio. This assumption makes their model far from the real world. Moreover, since we consider the associated businesses a real option, an option to invest in the associated business. This assumption makes Ingersoll's model, which values a financial option, more applicable than other models such as Hall and Murphy [5] or Carpenter [2].

3. THE VALUATION MODEL AND POLICY EFFECTIVENESS

Ho and Liu [6] applied real options framework in evaluating the financial viability of a BOT project. Ho and Liu [7] also discussed the added value to an investment due to the option to wait for investing, also called timing option. According to option pricing theory, if a project has options to decide the investment timing under uncertainty, the investment criteria will more stringent than the traditional non-negative NPV criterion since the project needs to have higher NPV in order to exercise/kill the option to wait, which is to invest by the definition of exercising an option. In the BOT scheme, typically the promoter has the right to decide when and how to invest in an associated business, and hence, has the option to wait. To price the land development right with options to wait, in the model we combine McDonald and Siegel's [12] model and Ingersoll's [8,9,10] model. McDonald and Siegel's [12] consider the investment with waiting option as a perpetual option, an option that will never expire. They find an investment threshold as shown in equation (1) so that when the benefit/cost ratio exceeds the threshold the investment is triggered. However, in many cases, the government will specify the length of time that the promoter can wait. To compute the timing option with limited option life, we incorporate Ingersoll's model for barrier option and use the threshold obtained from equation (1) as a proxy of the barrier in the pricing of a barrier option.

$$V/F = C^* = \frac{\varepsilon}{\varepsilon - 1} \tag{1}$$

where

$$\varepsilon = \sqrt{\left(\frac{1}{2} - \frac{\delta_f - \delta_v}{\left(\beta_x{}^2\sigma_m^2 + \xi_x^2\upsilon_s^2\right)}\right)^2 + 2\frac{\delta_f}{\left(\beta_x{}^2\sigma_m^2 + \xi_x^2\upsilon_s^2\right)}} + \left(\frac{1}{2} - \frac{\delta_f - \delta_v}{\left(\beta_x{}^2\sigma_m^2 + \xi_x^2\upsilon_s^2\right)}\right)$$

and

$$\beta_x \equiv \beta_v - \beta_f \quad \xi_x = \xi_v - \xi_f$$

$$\mu_x = r + \left(\mu_v - \mu_f\right) = r + \left(\beta_v - \beta_f\right)\left(\mu_m - r\right)$$

$$= r + \beta_x\left(\mu_m - r\right)$$

with

μ_v =the expected benefit of the associated business

δ_v =the shortage effect of real asset in benefit of the associated business

β_v =beta of benefit of associated business

μ_m =the expected return of total market

σ_m =risk of total market return

υ_s = nonsystematic risk of the BOT project

ξ_v =the correlation of benefit of associated business and benefit of main business

ξ_f = the correlation of cost of associated business and benefit of main business, assume $\xi_f^2 \to 0$

μ_f = the expected cost of the associated business

δ_f = the shortage effect of real asset in cost of the associated business

β_f = beta of cost of associated business

r =risk-free interest rate

Q_t =value of associated business when the option is perpetual

C^* =optimal investment-timing

Research on the effectiveness of manager's

compensation through stock options and their related assets shows that stock options are less valuable, compared to market value, to the manager when the options are offered as compensation and the trading of these options is restricted. The option value to the manager in this case is called "subjective value" in this paper. Usually, the subjective value will be smaller than the market value because the manger is forced to hold much larger portion, compared to the optimal portfolio without trading restriction, of the stock option offered as compensation. Such portfolio distortion caused by the liquidity restraint will limit the effectiveness of the motivation from compensation. Similarly, in a BOT project, considering the restriction on the promoter's project equity trading, when the promoter senses the trading restriction, the project will have a subjective value. According to Ingersoll [10], when computing the subjective value under options pricing framework, the risk free interest rate used for standard option pricing should be adjusted as shown in equation (2) to reflect the impact of trading restriction. However, there is another variable affecting the subjective value. This variable is the optimal investment timing calculated by equation (1) as we discussed previously. There are two situations in computing the optimal investment timing. The first one is when promoters make their own timing decision and the second one is when promoters make decisions based outside consultant's assessment. Since the outside consult does not have the share trading restriction, the outside consultant will suggests developing decisions based on the result standard option pricing framework, assuming that the consultant is professionally good and be able to assess the timing option and optimal investment timing. The timing obtained by the consultant is considered as "objective optimal timing." The second situation is when promoters make their own timing decision. Under project equity trading restriction, the computing of optimal timing in equation (1) is again affected by the adjustment of risk free interest rate by equation (2). Such investment timing is called "subjective optimal timing" in this paper. In other words, the subjective value of a land development depends on both the adjustment of risk free rate and the person who assesses the optimal timing. As a result, the value of the land development right to a promoter could either be the subjective value with objective optimal timing, denoted as Q_t'', or be the subjective value with subjective optimal timing, denoted as $\hat{Q}_t'$. As opposed to subjective value, the objective value of a land development right, denoted as Q_t', should be assessed from the market perspective, and therefore, be evaluated under standard option pricing framework with objective optimal timing. The meanings and characteristics of various types of values of a land development right are organized in Table 1.

$$\hat{r} \equiv r - (1-\gamma)\alpha^2 \upsilon_s^2 \tag{2}$$

where r =objective risk-free rate
γ =risk-aversion degree of promoter
α =liquidity restraint
υ_s =nonsystematic risk of the BOT project
$\hat{r}$ =subjective risk-free rate

By this adjusting, the subjective optimal timing could be defined as

$$V/F = C^* = \frac{\hat{\varepsilon}}{\hat{\varepsilon}-1} \tag{3}$$

where

$$\hat{\varepsilon} = \sqrt{\left(\frac{1}{2} - \frac{\hat{\delta}_f - \hat{\delta}_v}{\left(\beta_x^2\sigma_m^2 + \xi_x^2\upsilon_s^2\right)}\right)^2 + 2\frac{\hat{\delta}_f}{\left(\beta_x^2\sigma_m^2 + \xi_x^2\upsilon_s^2\right)}} + \left(\frac{1}{2} - \frac{\hat{\delta}_f - \hat{\delta}_v}{\left(\beta_x^2\sigma_m^2 + \xi_x^2\upsilon_s^2\right)}\right)$$

and

$$\beta_x \equiv \beta_v - \beta_f \quad \xi_x = \xi_v - \xi_f \quad \mu_x = \hat{r} + \beta_x(\mu_m - \hat{r})$$
$$\hat{\delta}_v = \delta_v + (1-\gamma)\alpha\upsilon_s^2(\xi_v - \alpha)$$
$$\hat{\delta}_f = \delta_f + (1-\gamma)\alpha\upsilon_s^2(\xi_f - \alpha)$$

From this formula we have built up several valuation models, as following:

Table 1 The valuation models

Value of a land development	Meaning	Option discounting system and the invest-timing
Q_t'	The objective value/policy cost for a land development right	Market risk free rate and Objective optimal timing
Q_t''	The subjective value for a land development right when the promoter makes investment timing decision based on outside consultant's suggestion	Adjusted risk free rate and Objective optimal timing
$\hat{Q}_t'$	The subjective value for a land development right when the promoter makes investment timing decision by themselves	Adjusted risk free rate and Subjective optimal timing

The structure of models are showed as follow:

Model-(1) $Q_t' = F_t \cdot C_{barr}$ (4)

with F_t =the expected optimal scale of land development, and

$$C_{barr} = \mathbb{C}\left(X,t;T;\{X_T>1\}\&\{X_{\max}<C^*\}\right) - \mathbb{D}\left(X,t;T;\{X_T>1\}\&\{X_{\max}<C^*\}\right) + (C^*-1)\mathbb{T}\left(X,t;T;C^*\right)$$

and

$$\mathbb{C}\left(X,t;T;\{X_T>1\}\&\{X_{\max}<C^*\}\right) = Xe^{-\delta_x(T-t)}\left\{\begin{matrix}\Phi(H(1))-\Phi\left(H\left(C^*\right)\right)\\ -\left(C^*/X\right)^{2(\lambda+1)}\left[\Phi\left(H\left(X^2/C^{*2}\right)\right)-\Phi\left(H\left(X^2/C^*\right)\right)\right]\end{matrix}\right\}$$

$$\mathbb{D}\left(X,t;T;\{X_T>1\}\&\{X_{\max}<C^*\}\right) = e^{-r(T-t)}\left(\begin{matrix}\Phi(h(1))-\Phi\left(h\left(C^*\right)\right)\\ -\left(C^*/X\right)^{2\lambda}\left[\Phi\left(h\left(X^2/C^{*2}\right)\right)-\Phi\left(h\left(X^2/C^*\right)\right)\right]\end{matrix}\right)$$

$$\mathbb{T}\left(X,t;T;C^*\right)=\left(C^*/X\right)^{\lambda-\kappa}\Phi\left(H_\kappa\left(C^*\right)\right) + \left(C^*/X\right)^{\lambda+\kappa}\Phi\left(h_\kappa\left(C^*\right)\right)$$

where $\Phi(\cdot)$=c.d.f. of standard normal distribution and

$$H_\kappa(z)\equiv\frac{\ln(X/z)+\kappa\sigma_X^2(T-t)}{\sigma_X\sqrt{T-t}}$$

$$h_\kappa(z)\equiv H_\kappa(z)-2\kappa\sigma_X\sqrt{T-t}$$

$$\lambda\equiv\frac{r-\delta_X}{\sigma_X^2}-\frac{1}{2}\qquad\kappa\equiv\sqrt{\lambda^2+2r/\sigma_X^2}$$

$$H(z)\equiv\frac{\ln(X/z)+\left\{r-\delta_X+\frac{1}{2}\sigma_X^2\right\}(T-t)}{\sigma_X\sqrt{T-t}}$$

$$h(z)\equiv H(z)-\sigma_X\sqrt{T-t}$$

$$\sigma_X^2=\beta_x^2\sigma_m^2+\xi_x^2\upsilon_s^2$$

$$\beta_x=\beta_v-\beta_f$$

$$\delta_x=r+(\delta_v-\delta_f)-\sigma_m^2\beta_f(\beta_v-\beta_f)+\xi_v\xi_f\upsilon_s^2 = r+(\delta_v-\delta_f)-\sigma_m^2\beta_f\beta_x+\xi_v\xi_f\upsilon_s^2$$

$$\xi_x=\xi_v-\xi_f$$

$$X_t=V_t/F_t$$

Model-(2) $Q_t''=F_t\cdot C_{barr}'$ (5)

The definition of factors in this model is just the same with model-(1), but the risk free rate is adjusted as shown in equation (2) to reflect the impact of trading restriction when discounting the asset value.

Model-(3) $\hat{Q}_t'=F_t\cdot\hat{C}_{barr}$ (6)

The definition of factors in this model is just the same with model-(2), but the optimal timing is adjusted as equation (3) to reflect the impact of trading restriction when promoters deciding the timing of investment.

Therefore, we evaluate the effectiveness of granting a land development by the ratio of subjective value to objective value. As shown in Table 1, we call the ratio Q_t''/Q' the "policy effectiveness for firms with land development expertise" and the ratio $\hat{Q}'/Q'$ the "policy effectiveness for firms without land development expertise." Next we will perform sensitivity analysis on several important factors/variables as shown in Table 2 to examine the policy effectiveness under different situations.

Table 2 Factors of sensitivity analysis

Factors	Meaning of factors	Type of factors
$T-t$	Duration	Project characteristics
β_V	Beta of benefit of associated business	Project characteristics
β_f	Beta of cost of associated business	Project characteristics
υ_S	Nonsystematic risk of the BOT project	Project characteristics
υ_V	Nonsystematic risk of benefit of associated business	Project characteristics
γ	risk-aversion degree of firm	Firm characteristics
α	liquidity restraint	Firm characteristics

The results show as follow:

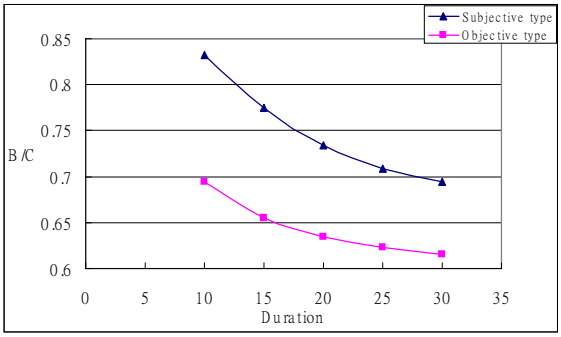

Fig. 1 S.A. of policy efficiency - $T-t$

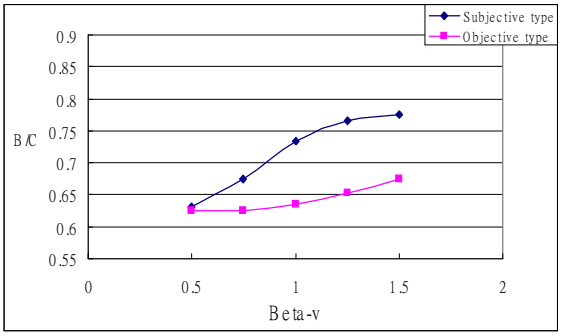

Fig. 2 S.A. of policy efficiency - β_V

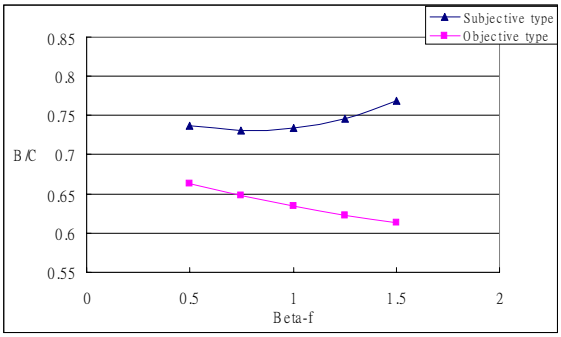

Fig. 3 S.A. of policy efficiency - β_f

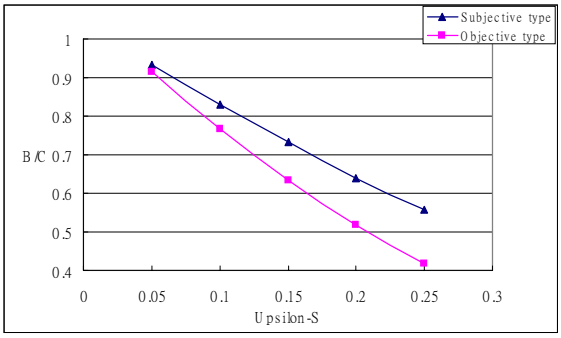

Fig. 4 S.A. of policy efficiency - υ_S

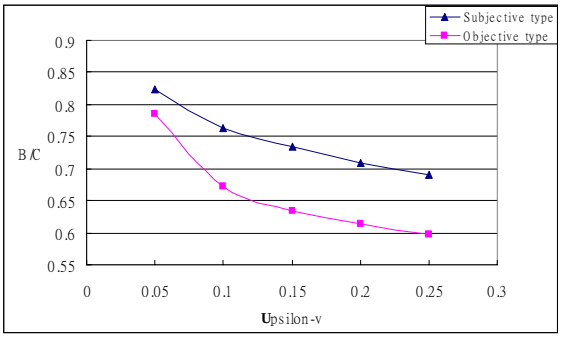

Fig. 5 S.A. of policy efficiency - υ_V

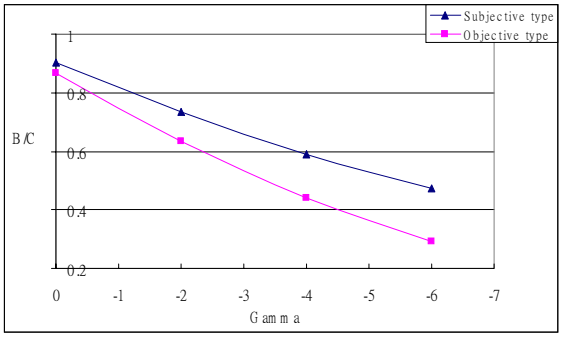

Fig. 6 S.A. of policy efficiency - γ

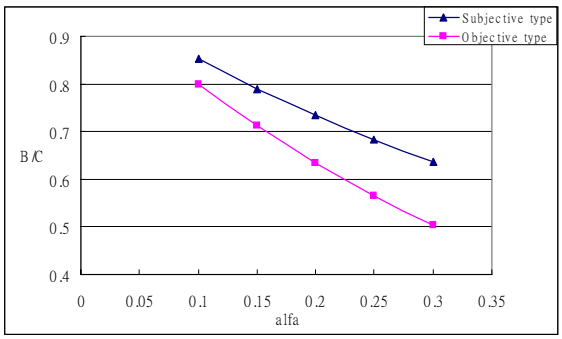

Fig. 7 S.A. of policy efficiency - α

The most important thing the government should concern when promoting a BOT project is 'policy efficiency.' However, people cannot probe into the motivating effects or policy efficiency without valuing the concessionaire's subjective values of these associated businesses in quantitative sense. So, in our research we build up valuation models of associated business. From the sensitivity analysis, we can get the result showing as follows:

Table 3 Analysis of policy efficiency

Change of factors	Meaning of factors	Change of policy effectiveness	Note: which type more significant
$T-t\uparrow$	Duration	$\downarrow$	Subjective type
$\upsilon_S\uparrow$	Nonsystematic risk of the BOT project	$\downarrow$	Objective type
$\beta_V\uparrow$	Beta of benefit of associated business	$\uparrow$	Subjective type
$\upsilon_V\uparrow$	Nonsystematic risk of benefit of associated business	$\downarrow$	Objective type
$\beta_f\uparrow$	Beta of cost of associated business	---	Not significant

Change of factors	Meaning of factors	Change of policy effectiveness	Note: which type more significant
$\gamma\uparrow$	risk-aversion degree of firm	$\downarrow$	Objective type
$\alpha\uparrow$	liquidity restraint	$\downarrow$	Objective type

From Table 3, we can find that policy efficiency will decrease if nonsystematic risk increasing. If other things remained, it means high volatility of net income before tax and interest of project will make policy inefficient. So the government should separate the firms with high volatility return from others. But usually the volatilities of projects are firms' private information.

5. Conclusions

From our research we find that several mechanisms will interact, such as that liquidity restraint will decrease the subjective value of associated business. The government should pay attention to this kind of interaction, or the motivating policy and ensuring policy will make each other inefficient.

Moreover, the government should not involve too much in the negotiation between potential promoters and banks, and the government should not limit the space of the outcome of interest rate in BOT projects. The financing contract could tell a lot of things about the type of a potential promoter, and the government should give more freedom to banks in negotiating with BOT firms to prevent the happening of adverse selection.

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BUILDING A WEB-ENABLED DATA WAREHOUSE FOR DECISION SUPPORT IN CONSTRUCTION EQUIPMENT MANAGEMENT

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Abstract**:** Construction equipment management and performance data are valuable assets for large contractors that need such historical data for decision making about resource allocation and equipment replacement; however, with large amounts of accumulated data, traditional data analysis based on a transactional system becomes increasingly inefficient. This paper summarizes a web-enabled data warehouse we developed for a local contractor, as well as the challenges we encountered in modeling and designing such a complex multi-subject Decision Support System (DSS). The methodology proposed in this paper is expected to provide a new approach to data analysis and information delivery in construction management.

Keywords: data warehouse, equipment management, decision support system, web application

1. INTRODUCTION

Standard General Inc. (SG) is one of the major construction contractors in Alberta. With its fast-growing business in equipment rental and road construction, SG developed Mtrack Equipment Management System (EMS) in collaboration with NSERC/Alberta Construction Research Chair in 1998. The new transactional system successfully replaced the traditional, error-prone bookkeeping and reporting processes used for equipment management. Mtrack EMS maintains a parts, fluids and fuel inventory service; stores a historical record of all the servicing performed on each of SG's fleet, which comprises more than 3,000 pieces of equipment; and can produce standardized work orders and more than 48 types of reports on equipment usage, costs, inventory and accounting.

Even though the Mtrack EMS tracks daily operations satisfactorily, the "reporting" functions became increasingly inefficient when large amount of data accumulated over the years of operations. Typical problems such as the following arise: large numbers of reports lack practical flexibility; analysis of some datasets depend on a large number of reports that are restricted with limited query-parameters and a fixed format; in addition, some reports run to as many as several hundred pages. As a result, large quantities of equipment performance and management data, which are valuable assets for the company, are difficult to interpret and prove to be of little value for decision support.

A web-enabled data warehouse can be a viable solution to these problems when considering a number of factors:

1) Data warehousing applications have been used to provide decision support in other industries for over a decade; its subject-oriented and multi-dimensional features fit very well in our application scenario.

2) The general trend of development is the complete separation of the operational system from the analytical system, the former manages Online Transactional Processing (OLTP) while the latter focuses on Online Analytical Processing (OLAP) [1].

3) A data warehousing system, like the Analysis Services in Microsoft SQL Server 2000, is more affordable and provides better cross-platform compatibility.

4) A web-enabled data warehouse has better accessibility, lower costs and requires less of client tools.

The Mtrack Decision Support System (DSS), based on data warehousing technology, has been designed and implemented in this research. The data report and analysis functions in the current Mtrack DSS have replaced those of Mtrack EMS. The paper summarizes our methodology, findings, and the challenges encountered in the design and implementation of this decision support system, with the focus on dimensional modeling and system design.

2. LITERATURE REVIEW

A pilot research project and the application of data

warehousing technology in construction were conducted by Chau et al. [2] at the University of Hong Kong. The authors built a Decision Support System (DSS) based on Online Analytical Processing (OLAP) for inventory management of construction materials. Based on its successful application to a residential building project, the authors concluded that a DSS that is based on data warehousing can produce more intuitive, multi-view information from the data depository than the traditional OLTP ad-hoc reports. In another case, Berndt et al. [3] reported on the CATCH data warehouse designed for community health decision support: the CATCH system revolutionized resource allocation and health care policy formulation in a comprehensive and systematic manner. The benefits of building the DSS warehouse according to the authors are: (i) Make it possible for local decision makers to organize and interpret the data clearly; (ii) Produce some core reports for local communities at a reasonable cost; (iii) In combination with web, the information can be presented in a variety of formats and distributed more widely in the community. However the authors of these two papers do not adequately address the high-level dimensional modeling and design required for a complex system.

Microsoft also incorporated data warehouse technology into its Enterprise Project Solutions (EPS) [4]. The Portfolio Analyzer in the Project Server allows the participants to analyze the project resources and performance data in the form of multi-dimensional OLAP cubes. It demonstrates that, for complex data structures in project management, a multi-dimensional view of project data provides superior performance over traditional method of data analysis and information delivery.

The Mtrack DSS distinguishes itself from other applications because it focuses on comprehensive subject areas to assess and model all operational processes. The system modeling and design aims to guarantee the final delivery of an integrated, non-volatile data warehouse characterized by easy access and high query efficiency.

In its technical aspects, the system takes advantage of the Microsoft's cutting-edge data warehousing technology, the multi-dimensional data access standard, Office Web Components (OWC) (distributed with Microsoft System Office 2003), and the .NET web development platform. Compared with traditional system implementation and deployment, the approach adopted by Mtrack DSS has a much lower development cost and a significantly shorter development cycle.

3. MULTI-DIMENSIONAL MODELING

Based on the current Mtrack Equipment Management System, a data warehouse was planned for the sole purpose of decision support. The objective was to help users gain insight into the equipment data along different dimensional views. Data warehousing is a proven technology for decision support, but it can serve this purpose only if the data warehouse is well planned, designed, implemented and deployed. With this in mind, we identified dimensional modeling and system architecture design as our top priorities. The following paragraphs will focus on the high-level design and modeling of the system, and the technical challenges they posed.

3.1 data warehouse Bus Architecture

Data Warehouse Bus (DWB) Architecture was proposed by Kimball and Ross [5]. So far, it is the most accepted method of data warehouse design. DWB architecture, presented in a bus matrix format, depicts an integrated picture of the whole system and represents a complete set of conformed dimensions and standardized fact tables. The bus matrix for Mtrack data warehouse is shown in Fig. 1.

1) The rows show the business processes in the system; each process contains interested measurements that serve as System Performance Indicators (SPI) in the fact table.

2) The columns show the conformed dimensions shared by various business processes. Kimball [5] defines the conformed dimensions as either identical or strict mathematical subsets of the most granular, detailed dimension [5].

The construction equipment management system in this research involves complex processes and resources that are no different from those in other construction activities. In this case, system modeling with DWB architecture demonstrates the following advantages:

1) All the processes with interested measurements are identified. The subject-oriented data warehouse is designed to collect, package and present the data accumulated in the business processes. The processes are clearly identified in the rows of the bus matrix.

Business processes	Common dimensions: the_Time	the_Class	the_Department	the_Account	the_Supplier	the_FuelType	the_FluidType	the_Parts	the_Employee	the_Manufacturer	the_Component	the_CostItem	the_RepairCostType
Fuel Consumption	X	X	X	X	X	X				X			
Fuel Inventory	X		X	X	X	X							
Fluid Consumption	X	X	X	X	X		X			X			
Fluid Inventory	X		X	X	X		X						
Parts Consumption	X	X	X	X	X			X		X			
Parts Inventory	X		X	X	X			X					
Purchase Order	X	X	X	X	X			X	X		X		
Work Order	X	X	X							X	X	X	
Repair Cost	X	X	X							X			X
Human Resource	X		X	X					X				

Fig. 1: Bus Matrix for Mtrack Data Warehouse

2) All the common (conformed) dimensions are identified: these dimensions are shared among various processes, so the dimension design will give due consideration to every process in terms of granularity, levels, properties, etc. If well designed, the shared dimensions will guarantee the data consistency and, most importantly, facilitate the data staging; as a result, the data ETL (Extract, Transform and Loading) efforts can be kept to a minimum.

3) The bus matrix can serve as a design tool, management tool and a communication tool [5].

3.2 Multi-dimensional modeling

In the DWB architecture, each row contains a set of measures for the corresponding business process and the associated common dimensions. The best model for this set of data structure can be modeled in a star schema, which includes a fact table at the center, and has all the connected dimensions arranged around it [5]. It models an interested subject in the system, with all the measurements in the fact table and all the data attributes in the dimension tables. The star-shaped data structure enables us to perform system performance analysis along one or along any combination of dimensions. Questions about the measured data addressing when, where, who, by whom, etc., can be answered after the schema is transformed into a dimensional data cube. Hence proper modeling of each star, with its underlying fact table and dimension tables, produces a complete view on the individual subject. All the stars in the system will collectively provide an integrated view of system performance.

In the Mtrack DSS, 10 stars are designed based on the DWB architecture, to model the different facets of the equipment management system. Fig. 2 shows the Repair Cost star schema, one of the most important subjects addressed by the system. The schema includes one fact table and five dimension tables:

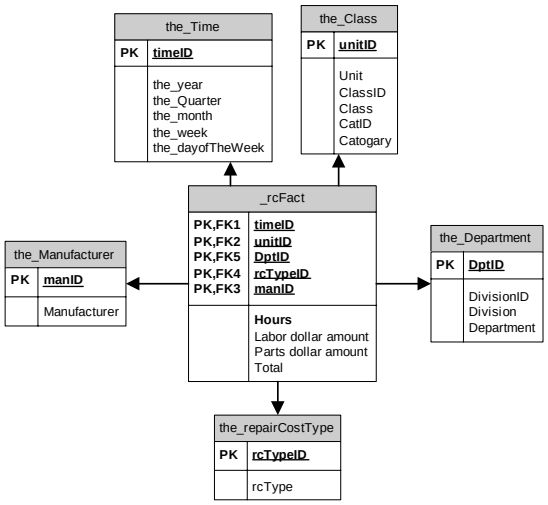

Fig. 2: Dimensional Model for Repair Cost

1) Fact Table: The measures included in the Repair Cost fact table are Hours Spend on Repair, Labor Cost Dollar Amount, Parts Cost Dollar Amount, and Total Repair Cost.

2) Dimension Tables: There are five dimension tables, including Time, Equipment Class, Department, Repair Cost Type, and Manufacturer dimensions. Each dimension has a number of attributes to define hierarchical levels, members at each level, and properties for each member.

All the reports on repair costs in the previous Mtrack Equipment Management System are now condensed

into a multi-dimensional data cube: the user can browse, drill down, roll up, or pivot the cost data in the cube along or across any combined dimensions. Examples of questions that can be answered with the system include: show the repair costs of all the earthmoving equipment for the year 2001; compare the repair cost of same class of equipment with different models and manufacturers for a particular period; and show the equipment that has the highest repair cost in a specific class.

During the design of Mtrack Data warehouse, we encountered the following issues that, when dealing with a complex system, must be properly addressed to guarantee the usefulness, efficiency, and non-volatility of the data warehouse:

1) Both the fact table and dimensional tables should focus on the most granular level of daily operations. The data warehouse differs from a database by delivering summarized information rather than a specific transaction; however, the data at the atomic level allows for a higher level view through roll-up, while data modeling at a higher level makes it impossible to drill down to get detailed performance data.

2) All the potentially interested measures in the subject should be included in the fact table. The data warehouse is designed for use by the people at different levels in the company; the more measures are included, the more the diverse needs of users can be satisfied.

3) Some semi-additive measures must be identified: for example, the fuel inventory volume in the fuel inventory fact table cannot be summed up along the time dimension. The cost variation percentage in the Work Order fact table cannot be added up along any dimension, so we choose *average* rather than *addition* for roll-up.

4) The concept hierarchy for each dimension should be properly modeled on and mapped to the dimension attributes or properties. This is the most practical step in order to make best use of measures in the fact table. If possible, all the dimensions shall be organized at different hierarchical levels in a top-down approach; for example, the Equipment Class Dimension has categories, classes and then units. Each unit in the dimension has properties such as the year of make, model, purchase date etc., so that users can compare equipment performance data according to categories, classes, and units, or compare equipment based on the equipment properties.

5) Shared dimensions shall be designed with due considerations to the needs of all the related subjects.

4. DATA WAREHOUSING

Data warehousing refers to all the steps required to build up the data warehouse. According to the dimensional model, these steps include: (i) Identification of data sources; (ii) Data staging, or data Extraction, Transformation and Loading (ETL) from the heterogeneous sources to consolidated data warehouse; (iii) Data presentation to the user via access tools. Fig. 3 shows the processes implemented in Microsoft SQL Server 2000 and the web-based front-end for user interaction with the Mtrack data warehouse.

We chose the Analysis Services in Microsoft SQL Server 2000 to build the data warehouse because of its low cost, high compatibility and ease of use.

4.1 Data Sources

Microsoft Access-based Mtrack Equipment Management System was first put to use in 1998. In 2001, a new SQL Server-based Mtrack EMS began to replace the access-version. This means the historical data sources of the Mtrack database include an Access database and a SQL-server database, their data structures differ slightly from each other.

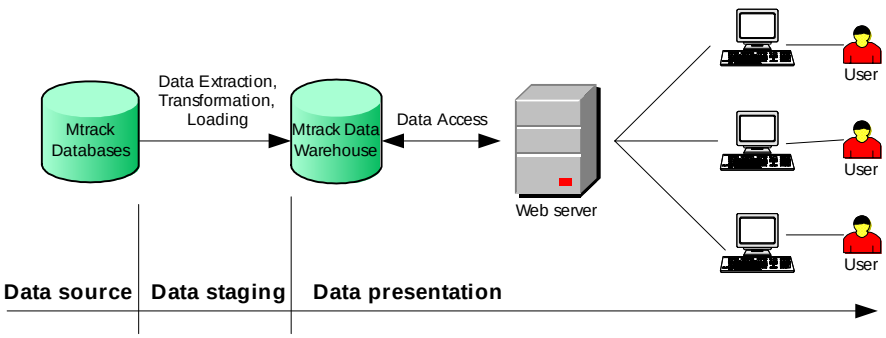

Fig. 3: Data Warehousing and Access

4.2 Data Staging

Data staging means to extract, transform and load the data from data sources to the data staging area. Kimball [5] defines the data staging area as everything between operational data sources and the data presentation area.

In Mtrack DSS, we use the Data Transformation Services (DTS) in Microsoft SQL Server 2000 to implement the data staging process. DTS is a set of visual design tools for data ETL. All the data sources, data validation, extraction and loading of data by SQL scripts, and e-mail notification of execution results can be visually designed as a package comprising a flow of processes. Scheduled execution of the package enables periodic updating of the data in the data warehouse.

A separate database in SQL server is created via the DTS package to provide a staging area where all the required data are cleaned and re-packaged for data presentation.

4.3 Data Presentation

The data presentation area is where the data is organized, stored, and made available for direct query by users, report writers, and other analytical applications [5]. Moving data from the staging area to the presentation area becomes a process of designing, building, and processing the data cubes according to the dimensional models in the data warehousing system.

With a complete set of wizards and visual tools, Analysis Manager in SQL Server Analysis Services makes it fairly easy to build the data cubes, and involves only three consecutive steps: data connection, data cube creation by dimensional model, and cube processing. The star schema for each subject appears in the Analysis Manager exactly as it is in the dimensional model.

After processing the cubes, the user can roll up, drill down, slice, dice, or pivot the data cube with the visual browsing tool in the Analysis Manager; however, to make the data cubes really useful, Multidimensional Expressions (MDX), the query language proposed by Microsoft [4] is needed to define and manipulate the multi-dimensional cubes.

5. MTRACK DECISION SUPPORT SYSTEM DESIGN

5.1 System Architecture

To publish the data cubes to the web and respond to user queries, the Mtrack web application is designed and hosted to work as a bridge between the user and the data warehouse. The technological platform for the communication process is shown in Fig 4. There are three physical parts in the system:

1) Database server: Pivot table service in the Analysis Server of SQL Server 2000 provides a set of client tools for the transfer of dimensional data from the data warehouse. Object Linking and Embedding Database for Online Analytical Processing (OLE DB for OLAP) and ActiveX Data Objects for Multi-dimensional (ADO MD) work as data access adapters for communication with the external applications.

2) Web server: the Mtrack DSS is designed as a web application with Active Server Pages (ASP) .NET development technology; the web server hosts the web application as an interactive web site so that users can query the data.

3) Web browser and Internet connection: the web browser is the only client tool required to communicate with the data warehouse.

5.2 Mtrack Web Applications

Fig. 5 shows a snapshot from the Mtrack web site, there are ten subjects available, each with four modes for data analysis: cube browsing, pre-formulated queries, user-defined queries, and data mining.

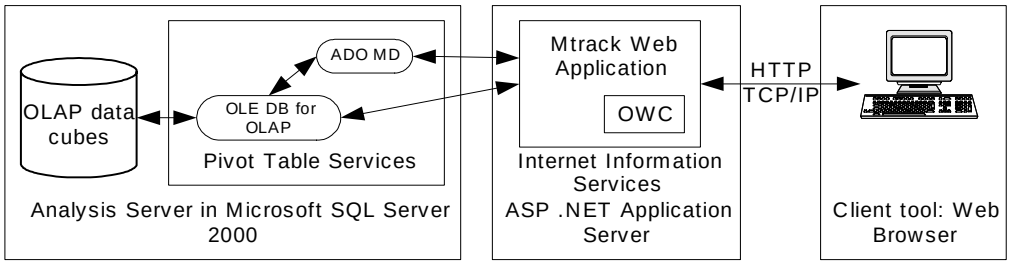

Fig. 4: Mtrack data warehouse system architecture

Microsoft Office Web Components (OWC), involving the pivot table and pivot chart, is embedded

in the web pages as ActiveX controls. These ready-use components provide rich interfaces for the visual browsing of data cubes with graphical charts.

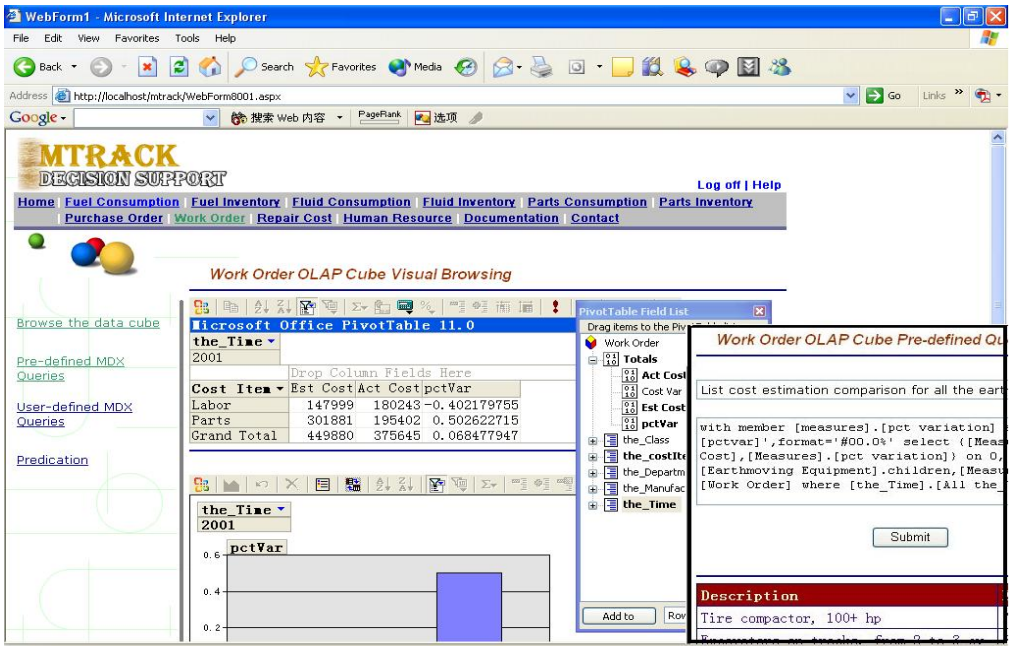

Fig. 5: Web Interfaces of Mtrack Decision Support System

Pre-formulated queries answer the most frequently asked questions on each subject; user-defined queries allow users to define the MDX query, and add it to the pool of queries if authorized to do so. According to Jarke [6], 80~90% of users will depend on cube browsing and pre-formulated queries for data analysis.

The data mining mode is intended for predication and classification based on the historical data. This will be implemented in the next stage of research.

6. CONCLUSIONS

Mtrack data warehouse completely changed the traditional way of analyzing the equipment management and performance data. By using the dimensional modeling and Online Analytical Processing, the system performance data are integrated in a superior structure for reporting and analysis. This paper presents the dimensional modeling and design of an integrated data warehouse for construction equipment management; a technological platform for deploying the data warehouse to the web is also proposed for quick application development.

Acknowledgements

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MINING OF CONCEPTUAL COST ESTIMATION KNOWLEDGE WITH A NEURO FUZZY SYSTEM

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Abstract: Conceptual cost estimation during the early stage of a construction project plays important role for feasibility analysis and project planning. Traditional approaches rely heavily on experienced engineers, and may cause loss of conceptual estimation knowledge of the firm. This paper proposes a method integrates a previous developed conceptual cost estimation method (PIREM) with the ANFIS neuro-fuzzy system for mining of cost estimation data. A case study of residential building projects in Mainland China is conducted to test the proposed method. The testing results show that the proposed method does not only achieve high system accuracy, but also provide many features desirable for estimators such as explicit fuzzy decision rules and graphical sensitivity analysis presentation.

Keywords: Conceptual cost estimation; Neuro-fuzzy; Data mining, KDD; China

1. INTRODUCTION

The conceptual cost estimation during the engineering planning is important for successful execution of a construction project, since the main structural systems, major construction methods, and most construction materials are determined in that stage. However, due to the lack of detail design information during the planning phase, accurate cost estimation is hard to obtain even for the professional estimators. It was found that the estimators with more estimating experience can do better in this job than who with less. The emerging development of modern artificial intelligence (AI) techniques, such as neuro-fuzzy systems, the aforementioned estimating experience/knowledge can be acquired by learning from historical examples, so that accurate estimation (compared with the detail estimation) could be obtained with very limited available project information. Unfortunately, an essential difficulty is facing the traditional conceptual cost estimation if the knowledge-based approaches are to be adopted—the unit prices of the cost items are variable in the marketplace, so that the estimation knowledge learned previously may not be readily applicable in the future projects.

In this paper, the PIREM (Principal items ratio estimation method) [1] approach is integrated with a neuro-fuzzy system, ANFIS [2], to perform data mining (DM) function in the knowledge discovery process of conceptual cost estimation. An application of the proposed DM method for cost estimation of building construction projects in People's Republic of China (PRC) is selected for demonstration of the proposed method in order to meet the needs caused by more and more construction projects invested by the Taiwan's businessmen in PRC in the past decade. As the cost estimation system of PRC (so-called "fixed price system [3]") is different from the cost estimation system in Taiwan (i.e., "bill of quantities", BOQ system), investors from Taiwan and other countries are unable to obtain accurate conceptual cost estimates for their projects, especially for the first-time investors. In order to conquer the difficulty, knowledge discovery in databases (KDD) [4] techniques are employed to mine the cost estimation knowledge from historical cost data of previous construction projects. The historical cost data are collected from sample projects in the publications published by the Ministry of Construction of PRC [5,6]. Totally, 114 building construction projects were collected and analyzed. The quantities and their unit price information of every cost item are surveyed and calculated separately in PIREM. The ANFIS neuro fuzzy system is adopted to capture the relationships between the influential attributes and the construction cost. The relationships acquired by ANFIS are stored in forms of fuzzy IF-THEN rules, so that the domain experts can visualize and verify the cost estimation knowledge explicitly. With the aid of the proposed approach, the barrier caused by different cost estimation system can be overcome. The testing results show that the cost estimation accuracy can be up to 90.01%, which is considered acceptable during the project conceptual planning phase.

The paper is organized in the following manner. In the second section, the previously developed PIREM approach for conceptual cost estimation is reviewed first to provide background knowledge. Then, process for mining of historic cost estimation data is briefly discussed. Fourthly, the ANFIS neuro-fuzzy system as a technique for data mining is introduced. In the fifth section, application of the proposed approach to cost estimation of building

projects in Mainland China is presented. Both data mining and system testing are presented and discussed. Finally, the findings of the research are concluded. Difficulties encountered in KDD of conceptual cost estimation, especially for cost estimation of projects in PRC, are discussed. Directions of future research are also suggested at the end of this paper.

2. PRINCIPAL ITEMS RATIO ESTIMATION METHOD (PIREM)

Among the many conceptual estimating methods, parametric cost estimating has been widely adopted in industry for the economic feasibility analysis in the early stage of a construction project. The parametric cost estimating takes important influential parameters as inputs, such as the floor area, cubic volume, bay width, etc. By statistic regression or other mapping schemes, the relations between the estimates and the influential parameters are established. The cost estimates of new projects are obtained by mapping inputs of parameter values based on pre-determined mathematic relation [1].

2.1 Problems facing traditional methods

The essential problem for all parametric cost estimating approaches is that the unit prices of cost items fluctuate as time passes. Thus, construction cost estimates obtained based on previous estimation experiences may be incorrect due to unit price variation in the marketplace. The key problem to this result is the use of "activity cost" as the measure of estimates during analogizing process. However, the "activity cost" mixes up the two elements—quantity and unit price—of a construction cost item. Even though some approaches introduced the "overall price index" as a parameter for adjusting construction costs [7], the price fluctuations for individual cost items are not varying proportionally and simultaneously. Adjusting the unit prices of all cost items with a "overall price index" is not realistic. The PIREM proposes a better way is to divide the two elements of the cost item and handle them separately. The quantities of a cost item are mainly affected by the factors of construction method adopted, such as the dimensions of structural design, the method of construction, the conditions of site environment, etc. Thus, they won't change as long as the same facility is constructed by the same method under the same environmental conditions. On the other hand, the unit price of the cost item may vary from time to time. It is reasonable to employ the most updated unit prices for the cost items in order to reflect the prices of marketplace.

Another problem is that a construction project usually consists of hundreds or even thousands of cost items. It is very expensive and time consuming to obtain the quantity estimates and unit prices of all items in a construction project. In order to resolve this problem, the PIREM adopts the Pareto Optimum Criterion (or namely, "80/20 Principle") to simplify the estimation process.

2.2 Model of PIREM

With the Pareto Optimum Criterion, only the top 20% cost items is selected as "*Principal Items* (PI)". The summation of the principal cost items gives the *Cost of Principal Items* (*PIC*). The ratio of *PIC* over the overall cost is defined as the *Principal Item Ratio* (*PIR* or *p*). The value of *p* can be calculated by the following equation.

$$p^s = \frac{\sum_{j=1}^{l} UP_j^s \cdot Q_j^s}{\sum_{i=1}^{n} UP_i^s \cdot Q_i^s} = \frac{PIC^s}{OC^s}, \qquad (1)$$

where the numerator is the summation of the costs of all *principal items*, while the denominator is the summation of the costs of all cost items in a project. The super script *s* upon all parameters stands for the s^{th} historical example. UP_i means unit price and Q_i means quantity of the i^{th} cost item, and so forth. *OC* stands for overall cost. The ratio *p* obtained in Eq. (1) is called *Principal Item Ratio* (*PIR*) as defined above.

It is found by analyzing *PIR*'s obtained from historical cost estimation data that the *PIR* of a specific type of construction project usually keeps constant with very small variation [8]. Therefore, given the *PIC*, the *OC* of the new project can be recovered by the following equation.

$$OC^r = \frac{PIC^r}{\overline{p}}, \qquad (2)$$

where OC^r is the estimate of overall cost for the new (r^{th}) project. $\overline{p}$ is the average *PIR* calculated from previous projects. PIC^r is the cost of principal items of the new (r^{th}) project.

In Eq. (1) and (2), the current unit prices (*UP*'s) for the new project should be surveyed from the marketplace at the moment of estimation. While, the quantity, *Q*, and average *PIR*, $\overline{p}$, have to be determined by parametric estimating methods based on the pre-determined mathematic relations. The mathematic relations between input parameters and the output estimate values are usually nonlinear. There are some approaches available for establishing such relations including nonlinear regression, artificial neural networks, and case-based reasoning. Among those, the nonlinear regression method may encounter severe convergence difficulty while dealing with more than two variables. The artificial neural network approach is good at nonlinear mapping. However, the mathematic relationships established are stored in a "black box" thus limits the value of knowledge learned. The estimation error of case-based reasoning method is still high [7], which may not be accurate enough for decision-making

during conceptual planning stage. In the proposed system, a neuro-fuzzy soft computing technique, ANFIS [2], is adopted to achieve more accurate estimations and provide human understandable knowledge for the estimators.

3. DATA MINING PROCESS

Data mining was defined as the application of automated knowledge acquisition methods for generation of useful knowledge via organization and analysis of raw data [9]. The procedure for data mining implementation consists of five steps [10]: (1) objective determination; (2) data preparation; (3) data transformation; (4) data mining; and (5) result analysis. There are some information techniques available for data mining implementation such as symbolic learning, case-based reasoning, and artificial neural networks. Two key issues for data mining are: (1) the accuracy of knowledge acquisition, and (2) the format knowledge representation. In this paper, a neuro-fuzzy system named ANFIS is adopted for mining of cost estimation data primarily due to the excellent learning ability and explicit knowledge representation of neuro-fuzzy systems.

Descriptions of the process for mining of historical cost estimation data are follows.

(1) Objective determination—the goal of data mining for cost estimation is to acquire the underlying knowledge embedded in the historical cost estimation data. Two primary objectives are providing accurate estimate of construction cost with a set of given parameters and the insight (inference process) of cost estimation.

(2) Data preparation—the "raw data" for cost estimation are collected from former projects and cleaned via a data pre-treatment process.

(3) Data transformation—the data transformation consists of two tasks: quantification of qualitative parameters and data normalization. This step is performed to prepare data for ready to use by the data mining techniques.

(4) Data mining—in this paper, the data mining process is performed by ANFIS neuro-fuzzy system. A commercial software — Matlab™ Fuzzy Logic Toolbox® — is adopted for mining of the historical cost estimation data. The raw data are divided into two sets: the training set and testing set. The grid partition scheme is used for fuzzy partition of input parameters. A hybrid-learning rule combining steepest descent scheme and least-square-error scheme is adopted for training of the neuro-fuzzy system.

(5) Result analysis—after training, the fuzzy decision rules are extracted from the historical cost estimation data for each training set. The rules can be used for system testing. They can be evaluated by the domain experts.

4. ANFIS NEURO-FUZZY SYSTEM

Neuro-fuzzy system is a branch of artificial intelligence (AI), which combines the merits of artificial neural networks (ANN) and fuzzy inference systems (FIS). A basic structure of an FIS is comprised of three components: (1) a rule base, which stores a bunch of fuzzy if-then rules; (2) a database, which defines the membership functions used in the fuzzy rules; and (3) a reasoning mechanism, which performs fuzzy inference upon the rules and given facts to derive a reasoning output or conclusion. There are three major types of FIS's widely adopted for management and engineering applications:

(1) Mamdani FIS—a general type of FIS that adopts "max" and "algebraic product" for fuzzy T-norm and T-conorm operations. A typical fuzzy if-then rule for Mamdani FIS is shown in Eq. (1).

$$R^k: \text{If } x_1 \text{ is } A_1^k \text{ and} \ldots \text{and } x_p \text{ is } A_p^k, \text{Then } y \text{ is } B^k, \quad (1)$$

where R^k means the k^{th} fuzzy rule; A_i^k and B^k represent fuzzy linguistic variables; $\bar{x} = (x_1, x_2, ..., x_p)^T \subset \Re^p$ and $y \subset \Re$ are the inputs and output of the k^{th} fuzzy rule.

(2) Sugeno FIS—a special type of FIS that adopts a crisp function in the consequence of a fuzzy decision rule. A typical fuzzy decision rule for Sugeno FIS is shown in Eq. (2).

$$R^k: \text{If } x_1 \text{ is } A_1^k \text{ and} \ldots \text{and } x_p \text{ is } A_p^k, \text{Then } y \text{ is } f_k(x_1, x_2, ..., x_p), \quad (2)$$

where R^k, A_i^k, B^k, $\bar{x} = (x_1, x_2, ..., x_p)^T$, and y are defined similarly as in Eq. (1), while $f_k(x_1, x_2, ..., x_p)$ is a polynomial taking on x_1, x_2, …, x_p and is used to define the consequence of a fuzzy decision rule.

(3) Tsukamoto FIS—also a special type of FIS that adopts a monotonical membership functions in the consequent part of a fuzzy decision rule. A typical fuzzy decision rule for Tsukamoto FIS is shown in Eq. (3).

$$R^k: \text{If } x_1 \text{ is } A_1^k \text{ and} \ldots \text{and } x_p \text{ is } A_p^k, \text{Then } y \text{ is } C_k. \quad (3)$$

where R^k, A_i^k, B^k, $\bar{x} = (x_1, x_2, ..., x_p)^T$, and y are defined similarly as in Eq. (1), while C_k are monotonical membership functions to describe the consequent part of a fuzzy decision rule.

While applying to data mining, the three FIS's mentioned above need to be equipped with "learning abilities" so that they are able to "mine" knowledge from raw data. Three popular learning schemes for constructing a neuro-fuzzy system are: (1) FALCON proposed by Lin and Lee [11], (2) ANFIS proposed by Jang [2], and (3) Back-propagation fuzzy system proposed by

Wang and Mendel [12]. In this paper, the ANFIS is adopted for construction of a Sugeno FIS.

5. APPLICATION TO RESIDENTIAL CONSTRUCTION PROJECTS IN CHINA

In this section, the proposed method is applied to cost estimation of residential building construction projects in Mainland China. The application is challenging in construction cost estimation due to the wide range of construction locations and variety of construction firms.

5.1 Fixed-price system in China

The "fixed-price system" is an outgrowth of the planned economy system of socialism, which aims at unifying the quantities and prices of a specific construction cost item by the government, so that the national economy can be under control [3]. In practice, the estimators of contractors usually prepare a "main resources list (MRL)" of the project while they submit their bids. Such MRL is very similar to the *PI* in PIREM described previously in this paper. With MRL, the managers are able to visualize cost profile of the construction project.

5.2 Why PIREM for construction cost estimation in China?

PIREM has been successfully applied in the public construction cost estimations in Taiwan [8]. The aptly separation of quantity and unit price of the cost item has demonstrated its capability in reflecting the most updated currency in marketplace. The "fixed price system" of Mainland China also separates the quantity with unit price determined by the government—the "fixed price", thus shows great similarity with the scheme of PIREM. The other reason for adopting PIREM is the wide range and great variety of China's construction market. Since China is one of the largest countries in the world, it is difficult for a contractor to develop specific estimation system for every province or city. PIREM provides a universal conceptual cost estimation method for contractors who perform projects in different provinces or cities in China.

5.3 Historical databases

In order to acquire the cost estimation knowledge, historical data of 110 high-rise residential construction projects from China are collected from a government publication [5,6]. The location distribution of the 110 projects is shown in Figure 1. The 110 projects are selected from 25 provinces/cities, where the top five provinces/cities are Beijing City, Fujian Province, Hebei Province, Hunan Province, Sichuan Province, and Shaanxi Province.

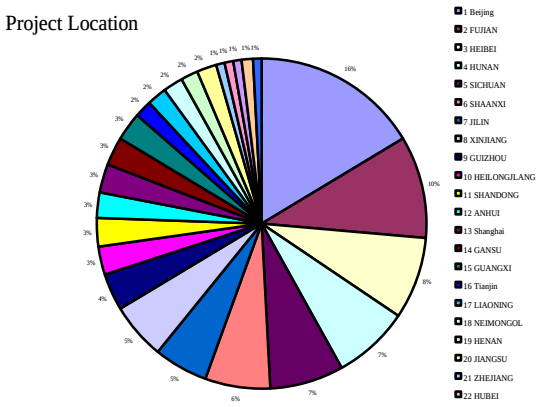

Figure 1. Distribution of project locations

The cost volume distribution of the110 projects is shown in Figure 2. In Figure 2, it shows that the construction costs of the historical residential projects are uniformly distributed.

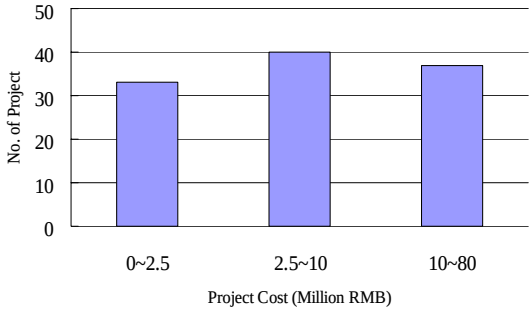

Figure 2. Distribution of construction costs

By statistic analysis, the MRL of the 110 residential construction projects consists of 10 elements: labor, cement, rebar, gravel, sand, brick, structural steel, tile, wood, and glazing, which will be considered for principal items (PI) of PIREM.

5.4 Verification of ANFIS data mining

To verify the nonlinear mapping of ANFIS, historical data were collected and divided into two sets: (1) 110 data sets collected from reference are used for training, and (2) the other 10 data sets collected from reference are used for testing. The training error is controlled within the error goal of 10%. The maximum epochs for training are controlled within 1000. The training and testing are performed for all principal cost items. The testing errors are within 10% (9.99%). The system accuracy is generally satisfied, since the acceptable error for a conceptual estimation system usually ranges from 15%~20% [13]. The results for the 10 testing sets are shown in Table 1, where the foundation types consist of: (1) simple foundation (value=1); (2) continuous foundation (value=2); (3) shaft foundation (value=3); (4) box foundation (value=4); (5) PC pile (value=5). Moreover, the structural types include: (1) brick (value=1); (2) RC frame (value=3); (3) shear wall (value=5).

Table 1. Results for testing sets

No.	PIC*	P%	Actual cost*	Estim. cost*	Acc. %
1	290	47.70	556	607	90.88
2	564	51.70	1057	1091	96.75
3	292	45.30	626	645	97.08
4	491	42.10	1015	1166	85.19
5	324	46.30	610	700	85.37
6	503	42.30	1018	1189	83.13
7	232	53.60	462	433	93.65
8	459	45.90	1114	1000	89.75
9	488	44.70	1224	1091	89.20
10	596	45.60	1179	1306	89.15
Average accuracy %					90.01

* RMB/M^2

5.5 Influence of price fluctuations

In order to assess the influence of price fluctuations in the market, two scenarios are designed for sensitivity analysis: (1) all unit prices of principal items are increasing while the non-principal items are decreasing; (2) all unit prices of principal items are decreasing while the non-principal items are increasing. Each of the above scenarios is analyzed under three ranges of price variation, that is: (1) unit prices randomly varying from 0~5%; (2) unit prices randomly varying from 5~10%; and (3) unit prices randomly varying from 10~15%. The price variation ranges is compared with the price fluctuations observed from the market shown in Table 2. It's found from Table 2 that the maximum price variation of China's market is below 5%. Therefore, the sensitivity analysis should cover all possible price fluctuation ranges that may happen in the near future.

Table 2. Price fluctuations of China, 1996~2001 [14]

Year	Consu. index	Retail index	Manu. index	Matl . index	Fixed prop. index
1996	100.00	100.00	100.00	100.00	100.00
1997	102.81	100.79	99.68	101.30	101.69
1998	101.98	98.17	95.60	97.02	101.47
1999	100.55	95.24	93.29	93.83	101.07
2000	100.95	93.81	95.92	98.62	102.20
2001	101.65	93.07	94.68	98.40	102.59
Fluct.	1.56%	4.34%	4.40%	2.79%	1.77%

Table 3. Testing of unit price fluctuation

Scenario	Unit price variation	Ave. accuracy.	Error increase
Scenario I ([1]PUP↑, [2]NUP↓)	0%	90.01%	0.00%
	0~5%	90.98%	↑ 0.97%
	5~10%	88.08%	↑ 1.93%
Scenario II ([1]PUP↓, [2]NUP↑)	0%	90.01%	0.00%
	0~5%	91.45%	↓ 1.44%
	5~10%	90.09%	↑ 0.08%

[1]PUP: Unit prices of principal items
[2]NUP: Unit prices of non-principal items

The proposed system is also tested to view the influence of unit price fluctuation on its estimation accuracy. The testing results are shown in Table 3. Where, under the worst scenarios, the highest error is still below 20%, the margin of maximum allowable error for a conceptual estimation system [13].

5.6 Sensitivity analysis

One of the most valuable features for data mining is the graphical presentation of the minded patterns or knowledge. For cost estimation, user always wants to know the most sensitive factors affecting the construction cost. In this regards, sensitivity analysis of various influential attributes on overall construction cost is very useful for value engineering and best alternative selection. Figure 3 and 4 show examples of sensitivity analyses, where the red color indicates areas that are potentially costly and should be avoided. Moreover, sensitivity analysis can also help users identify cost sensitive attributes. For example, the foundation type is more cost-sensitive than structure type and floor area in Figure 3; the number of stories is more cost-sensitive than structure type in Figure 4.

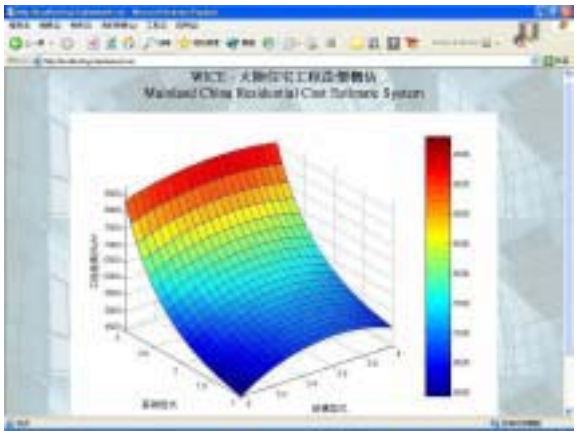

Figure 3. Sensitivity Analysis—Foundation type vs. Structure type

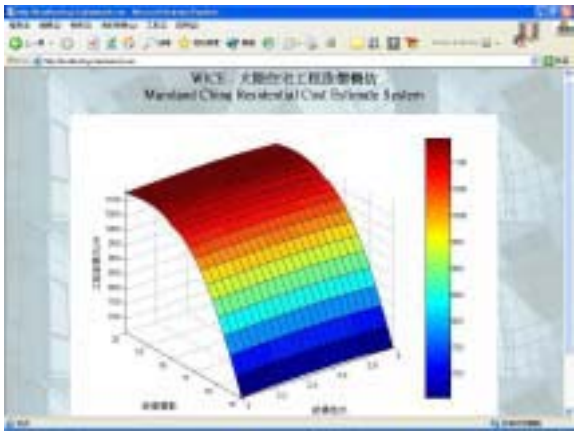

Figure 4. Sensitivity Analysis—No. of stories vs. Structure type

5.7 Fuzzy rule base

The knowledge mined by ANFIS is stored in the fuzzy rule base such as the one shown in Figure 5. The fuzzy rule base contains a set of fuzzy decision rules. Every fuzzy decision rule consists of a set of fuzzy linguistic terms for expressing values of every attribute in the precondition part; it also contains a set of fuzzy linguistic terms for the single output in the consequence part. Every fuzzy linguistic term is coupled with a fuzzy membership function. The fuzzy decision rules can be visualized and evaluated manually by the domain experts.

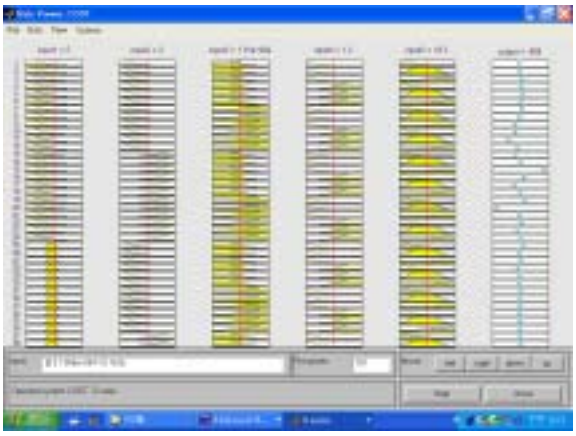

Figure5. Fuzzy rule base

6 CONCLUSIONS AND RECOMMENDATIONS

This paper presents a data mining method for mining of construction cost estimation knowledge. The proposed method integrates a conceptual cost estimation method (PIREM) with a neuro-fuzzy soft computing data mining technology (ANFIS) to provide desirable features for construction cost estimation. While applying to the geometrically huge and geographically complex construction market such as China, the proposed method demonstrates its outstanding capabilities in knowledge discovery. It provides not only the accurate estimation results but also the visual knowledge representations that are useful and desirable for the users. A case study of residential building construction projects in Mainland China is demonstrated to test the proposed method. The testing results show that the proposed method can still achieve high estimation accuracy up to 90.01% even for the great variety market such as China.

Some future directions for research can be pursued: (1) application of proposed method to other types of projects, such as industrial projects logistic inventory projects, infrastructure projects, etc.; (2) integration of proposed method with construction planning and scheduling systems to expedite project execution; (3) development of a more intelligent data mining technique to improve the estimation accuracy.

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The Application of Knowledge Map in Construction Knowledge Management

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Abstract: Knowledge map is one of the most important and useful tools in the knowledge management field. Knowledge map can be used to effectively plan the implementation of a knowledge management strategy for a term, department, and enterprise. With the assistance of knowledge map, users cannot only easily understand and identify where the knowledge in located in the system, but can also determine what intellectual assets are essential to their enterprise. The methodology uses a knowledge map as a tool to represent knowledge in implementing construction knowledge management effectively. The main contents of this paper includes (1) study current knowledge management and map application system's function and characteristics; (2)propose the process for creating a construction knowledge map; (3) propose important factors and analysis in knowledge map design. Furthermore, a construction classification structure is provided in the paper and a scenario is explained to describe the framework of building construction knowledge map by studying review literature and experts symposium.

Keywords: Knowledge Management; Knowledge Map; Construction Industry; Construction Project.

1. Introduction

Knowledge map is a very important field of study in the knowledge management field. One of the most important parts that construction industries focus on is how to extract tacit knowledge in the enterprise. Knowledge map is an important connection to improve knowledge exchange. The main contains of this paper include (1)study current knowledge management and map application system in function and characteristics; (2)propose the process for creating construction knowledge map; (3)propose important factors and analysis in knowledge map design. Furthermore, a construction classification structure is provided in the paper and a scenario is explained to describe the framework of building a construction knowledge map by studying literature reviews and consulting experts' symposia.

1.1 Characteristics of Construction Environment

Construction projects are usually unique. The characteristics, specifications, and execution plans of construction products are described in a large number of construction documents, such as contracts, specifications, meeting minutes, change orders, field reports, requests of information, drawings, schedules and cost estimates. In addition, there are not only many different kinds of positions as owner, designers in project team members, contractors and other stakeholder organization,, but also many kinds of file types such as structured data files, semi structured data files, unstructured text data files, unstructured graphic files and unstructured multimedia files. All of these contain a vast a mount of tacit knowledge. However, users often have difficulty obtaining and reusing such tacit knowledge.[2][3]

1.2 The Benefit and Characteristic of Knowledge Map

The main benefit and characteristic of knowledge map can summaried in the following [2]:

(1). Decision maker can know where the knowledge resource is.
(2). Help decision maker to confirm the scope of the industrial knowledge demand.
(3). Help decision maker to make the relative decisions about industry knowledge's assets.
(4). Help the superintendent to plan more a effective employee training program.
(5). Decreasing the employee's training program process to improve efficiency.
(6). When the strategies change, knowledge map can fulfill its function.
(7). Let each know their progress in the learning schedule.
(8). Compare the requirements and the achievements of industrial knowledge.

Besides, there are seven kinds of knowledge management maps listed the characteristic in Table 1.

2. Research Methodology

This paper discusses how to apply knowledge maps in construction knowledge management. In current practice the Construction and Planning Agency in Taiwan established a committee group call "Construction Knowledge Management Map Project" to assist the construction industry in implementing knowledge management. The research consisted of conducting several expert symposia held by a committee group. The result of symposia is summarized in this paper.

3. Construction Knowledge Management Map Project

The Construction and Planning Agency in Taiwan have the "construction knowledge management map project", witch not only establish the committee group, expert symposia ,and create a construction knowledge classification structure, but also set up the principles for construction knowledge map. All of the project execute are the important basis for implement knowledge management in construction industry.

3.1 The committee group

This research project includes 13 committee members at present time. The members were selected according fo their knowledge of a specialized domain, the combination of theory and practice in the construction industrial area and management group and so on.
In order to successfully establish the knowledge map, classification of construction, and the knowledge exchange standard, the committee must have a rich background in information development and combined fields. It must also have a suitable background in industry theory and also have multitudinous experiences in construction knowledge classifications, as well as the dynamic information platform plan and operation and so on, so that they can be of assistance in integration into the construction knowledge management knowledge base.

3.2 Construction industrial classification structure

Knowledge classifications structure classifies and codes the knowledge item in construction engineering in a systematic manner. Its main goals are to standardize the construction industry knowledge classification construction, and to integrate and store the information using codes. In this way, information can be made available to all and used more effectively.
Subsequently, this paper discusses the internal and foreign classification systems such as OCCS and UniClass. It also proposes the basis for the construction knowledge management system management code, as show in Table2 [2].

3.3 Brief introduction of construction industrial knowledge map

Research on related information about construction engineering is difficult to obtain. Moreover the overall information survey is unclear. Therefore, this research emphasizes the construction of a knowledge map.
The aim of this project is to establish a knowledge encyclopedia and knowledge map inquiry, reduce the scope inquiry and information survey, use a multi-construction method, and confirms the relationship among information.

3.4 The industrial classification construction principles

This study forms the foundation of a knowledge map by using academic classification constructions as a reference: Basically, construction industrial classifications take the static state, fixed, the less degree of change as the basic consideration for the classification constructions. If there is not a complete basic construction, creating a brand-new classification construction will be a heavy cost, high error taken and investment reward rate behavior.
Except for the basic static classifications, the construction industry and the database users needs grow. If the knowledge base classifications application is limited, the database cannot be able to provide its outstanding function. Therefore, this study suggests using the combination of both static and the dynamic knowledge classification construction.
For example, a certain knowledge documents have been about excavated in the basement store up in some knowledge platform. This document has a high possibility of being related to material document concerning the owner, the construction company, the consultant firm, general constructor, the material supplier or the specialized contractor and so on. If only regarding the document as a structural engineering document, we will be retrieve it by unable to another path. It will cause enormous limitations in the application of this knowledge platform. Therefore, the dynamic construction industrial classification constructions will become a long-term execution strategy and goal for this research.

3.5 Principles for construction knowledge map

(1). Branches of the first classification construction layer should contain no more than ten categories; Branches of the second classified structure layer contain at least seven but no more than ten.

(2). In the initial establishment of knowledge classification construction,a specialized group of experts discuss together first, and then,according to by the different position, choose the most valuable knowledge construction of each group.
(3). The knowledge documents of the training groups: First, take 30 articles as the training group from the branches of each classification construction. Each article shoule be a standard in the article length of less than 20 pages.
(4). Testing knowledge documents of the groups: Take 20 articles as the testing group from the branches of the each classification construction. Each a article should be a standard length of less than 20 pages.
(5). After passing the system test, the results still needed to be given as feedback to the experts for them compare and analyze.By doing so, the system could be updated to carry out the classification result.
(6). Knowledge maps establish axis by integrating three dimensions: project specialized technology, project application and life cycle.

Building a construction of the knowledge map materials classification could explain in different angles. First, focus on the industrial application project items, including construction, water resources, transportation and so on. We could conclude another knowledge technical classification dimension from the above classifications, like laws and regulations standard, construction management, structure engineering, geotechnical engineering, surveying engineering and environment engineering and so on. On its overlapping spot means it has the knowledge correlation of plan and the execution part. On knowledge correlation spot brings out the issue of grows plan, the design, the construction, the sustainable operation management, thus unfolds another construction management related dimensions. On the knowledge related crossover point, brings out the specialty tree shape knowledge structure and organizes a thorough knowledge network.

4. Building scenarios analysis of knowledge map classification structure

Stage1: The analysis of demand

[Step 1] Investigate the knowledge classification structures that fit into the knowledge management organization's interior needs and implement it into the knowledge-managed organization. Then download the standard knowledge classification template from the Construction and Planning Agency, as show in Table3 and Figure2.

Stage2: The beginning of implementation

[Step 2] Revise the classification structure until it belongs only to this organization by using the download classification template and the classifing situation in organization.
[Step 3] After revising the needed classification structure, choose different dynamic knowledge maps that fit into each department in organization.
[Step 4] Use the knowledge classification structure and knowledge map, established in the current stage, as the important foundation for knowledge implementation. Then add the knowledge encyclopedia provided by the Construction and Planning Agency as the knowledge resource from outside the organization, as show in Figure3.

Stage3: Mature application

[Step 5] In the mature application process, the main basis for judgment lies in tranforming, through knowledge classification and treatment, the company's existing knowledge documents into an existing knowledge management system. By doing so, is established the unique company's unique knowledge encyclopedia, as show in Figure4.

Stage4. Internal sharing and creation stage

[Step 6] After integrating the knowledge encyclopedia that was provided by Construction and Planning Agency and the company existing knowledge documents, share it among all members of the company simultaneously, or hand it over to the specific knowledge community to apply it and maintain it. Furthermore, create an updated knowledge document, and feed it back into the company interior system, as show in Figure5.

Stage5.External dynamic renewals and feedback stage

[Step 7] Of the exterior organizations like the Construction and Planning Agency and so on, update the established company interior knowledge encyclopedia, and feedback the information that is allowed for publication back to the organization or the trade union of the same business.
[Step 8] Feed the knowledge map that was revised for the company interior needs back to the Construction and Planning Agency as the brand-new inducts reference model inorder to enhance the knowledge map application benefit.
[Step 9] Feedback the knowledge classification structure which has been applied by company to the knowledge classification structure owned by the Construction and Planning Agency, and provide it as an important reference to the application of the companies in the same business, as show in Figure5.

5. Conclusion

Knowledge map application use information techniques such as document classification, information inquiry, and visualized information, etc. This article dose not focus on the theoretical application of each information technology, but rather establishes and explains knowledge map's application models through experts' discussion and situational analysis. This main reason for this is to expand and strengthen the knowledge map concepts and to extend its applications. However, the related research fields, such as document classification, information inquiry, visualized information and other information techniques should not be ignored. The way to bring out knowledge map's concept in construction industries is to establish a unified construction industries classification structure, construction thesaurus, as well as integrating and gathering all kinds of knowledge documents.

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Table1 Current knowledge map characteristics

Type	An expression introducing comparison
The file explorer	Instruction: This type uses a knowledge tree to show how knowledge is distributed. This type could convenience the user by providing a fast and direct understanding of knowledge classification and the distribution. This type of the existing knowledge map is often uses and applied. Advantages: Clear and fast direct understanding knowledge classification and distributed situation. Shortcomings: This type is unable to use three-dimensional spaces to demonstrate the knowledge classifications and distribution. It is also unable to express the correlation degree among different knowledge types.
The mind map	Instruction: Mind map expresses the knowledge distribution with the knowledge tree similar to the human's thinking pattern. This type convenience the user by directly providing an understanding of human's thinking patterns' distribution and the content. This is one of the existing knowledge map display types. Advantages: Clearly expresses the pattern of human thinking. It could reduce communication gaps. Shortcomings: It is not easy to express multi-dimension, using this type is also unable to express the correlation degree among different knowledge types.
The netted map	Instruction: The netted map type shows the knowledge distributions using the netted map. This type is convenient because it allows the user to directly understand the main classifications of knowledge and its correlation. It is generally applied to high correlation website content's linking. Advantages: Provides a understanding of fast and direct knowledge correlation and distribution. Shortcomings: It is not easy to express multi-dimensional knowledge using this system. It is also unable to express the correlation degree among different knowledge types.
The listed map	Instruction: This map expresses knowledge distribution by listing them. This type is convenient because it allows the user to directly understand the knowledge classifications and the distribution condition types. Fast construction is also the main superior of the listed map. It is also one of the early knowledge map applications. Advantages: The user is able to understand clearly knowledge classifications. Shortcomings: It is unable to express the main scatter situations of knowledge. It is also unable to show the correlation degree among different knowledge types.
The bio tree map	Instruction: This map shows the knowledge distribution by using a scattered map knowledge tree. This type is mainly used to express the knowledge type classifications. Through the density and the distance among spots, the map shows the knowledge map. Advantages: The user is able to understand clearly knowledge classifications and distribution situation. Shortcomings: It is not easy to express multi-dimensional knowledge. It is also unable to express the correlation degree among different knowledge types.

Type	An expression introducing comparison
The star tree map	Instruction: This map shows the knowledge distributions by a star shaped map. This type lets the user have a clear understanding of the main knowledge distribution classification and its sub-classifications. It is one of the most often-used application tools in present knowledge maps. Advantages: This type can show clearly the knowledge classification and relations. It may also facilitate the expression of the correlation degree among different knowledge types. Shortcomings: It is unable or uneasy to express the correlation degree among different knowledge types.
The contour line map	Instruction: This map shows the knowledge distribution by the contour line map shaped by knowledge tree. This type is an application of three spatial expressions and the contour line concept. It has the key advantage of visualizing the knowledge map. Advantages: In three spatial expressions way, this map could improve the main barrier to visualization. It ables the user to understand the knowledge classifications and distribution situation in a non- abstract way. Shortcomings: This type is unable to express the correlation degree among different knowledge types.

Table2 Existing construction industrial classifications construction

Items	Classifications introduction
The project classification	Owner (includes personally and government units), the construction company, the consultant firm, general constructor, material supplier, specialized contractor, specialized technician office
academic classification	Classify by the domestic and foreign academic specialized knowledge. The main knowledge classification constructions are the architecture, the urban plan, the environment engineering, the structural engineering, the geotechnical engineering, the surveying engineering, the hydraulics engineering, transportation engineering, the material engineering, construction management and so on.
Others	OSSC, UniClass, construction patent and so on.

Table3 Scenarios analysis of knowledge map classification structure

Knowledge Management Application Stage	Knowledge Classification		Knowledge Type
	Classification Structure	Knowledge Map	Knowledge encyclopedia
Demands analyzing stage	**Step1**		
Start implementation stage	**Step2**	**Step3**	**Step4**
Mature applications stages			**Step5**
Internal shares and the creation stage			**Step6**
External dynamic renewals and feedback stage	**Step9**	**Step8**	**Step7**

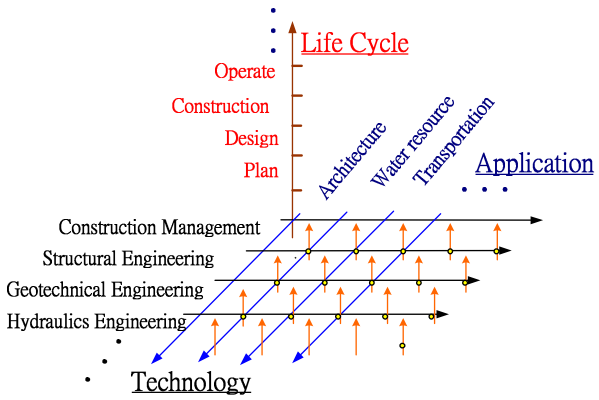


Figure1 Three dimensions of construction knowledge map matrix

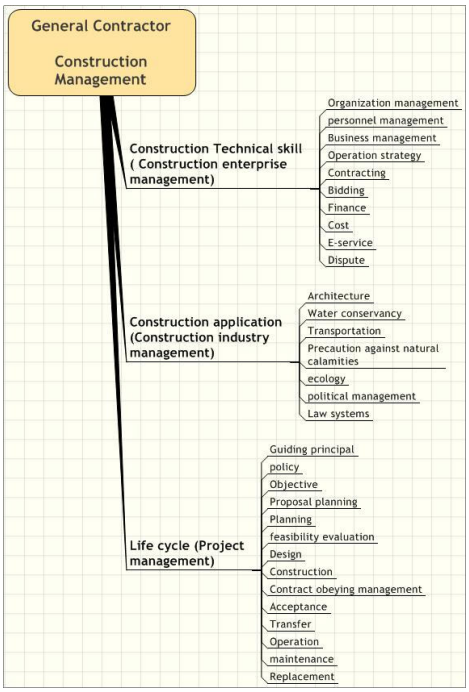
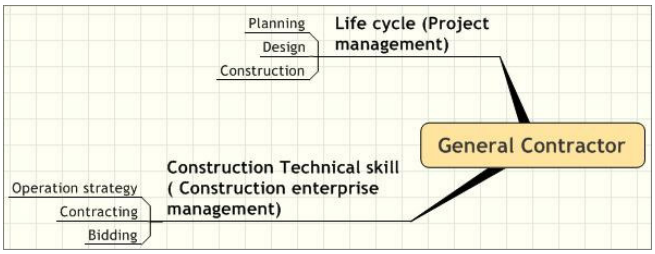


Figure2 Demands analyzing stage



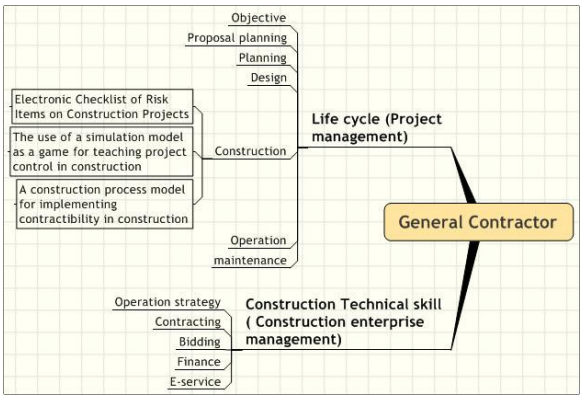


Figure3 Start implementation stage

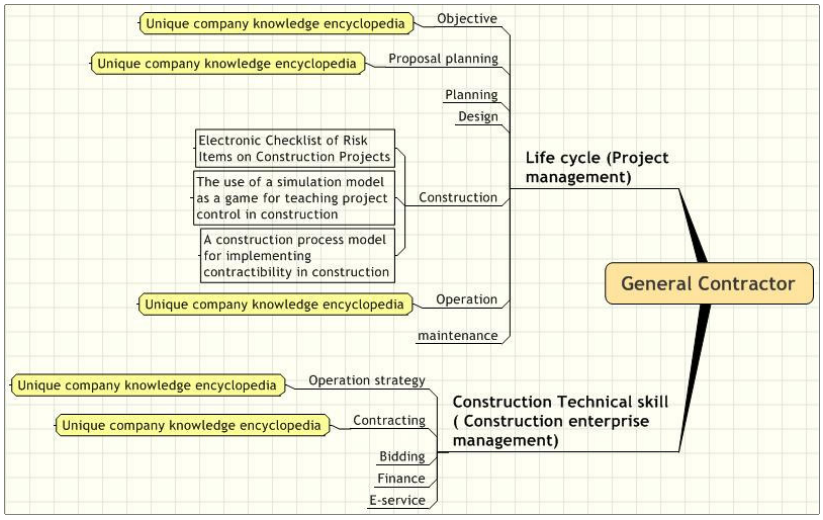


Figure4 Mature applications stages (unique company knowledge encyclopedia)

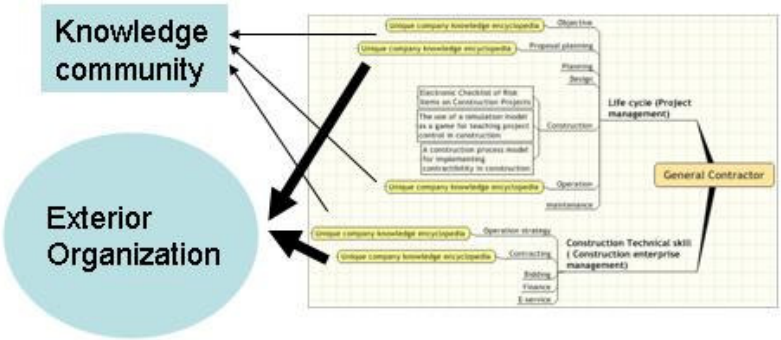


Figure5 Internal shares and the creation stage (knowledge community)
External dynamic renewals and feedback stage (exterior organization)

COST-EFFECTIVE ROBOTS FOR FAÇADE CLEANING

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Abstract: In the last years, several robots for building façade cleaning have been designed and some prototypes have been developed. However, most of these robotics systems are too expensive to be introduced in the market or are only able to cope with very simple completely flat glass façades. Funded by the European Commission, a consortium formed by several European enterprises and research institutions is developing a semi-automatic low cost robotic system that is able to cope with the cleaning tasks of most of the existing large building façades. The robotics system is semi-automatic because one single human operator is necessary to supervise the robot task and to perform simple operations. However, this operator, located at the ground, increase the security of the cleaning task. The main specifications for a marketable robotic façade cleaning system are presented and after that, a first description of the proposed robot is presented, showing the concept of the system and the control architecture.

Keywords: Automatic Façade Cleaning, Climbing Robots, Cleaning Robots.

1 INTRODUCTION

Nowadays the number of buildings with large glass or flat façades is increasing all over the World. These façades must be periodically cleaned with manual procedures that supposed high cost and risk for the workers which have to develop their work under heavy conditions. Although the cleaning cost depends a lot on several factors as the façade characteristics, the cleaning periodicity or the total surface to be cleaned, the cost per square meter, in Europe, varies between € 4 for flat glass façades and € 18 for jalousies and difficult structures. The average cost is € 7-8 per square meter. A typical building of 12.000 m^2 supposes a total façade cleaning cost of € 100.000 and this task is usually done every year. The use of an automatic or semi-automatic cleaning system can lead to around 60% savings over existing practice. In the cleaning of a single building, a saving of the order of € 50.000 will be possible, for example.

Automation and robotics technologies allow environmentally friendly façade cleaning, helping to reduce the cost of these tasks. Additionally, these systems overcome the current worker safety problems associated with difficult and dangerous access, contributing to a zero injury and fatality working practices [1].

Because of the increasing number of high-rise buildings and large glass façades and the resulting problem of safe and effective cleaning, a lot of effort has taken place in the last few years to develop automated cleaning systems. The majority of systems conceived and developed thus far are in Japan [2] and Europe [3]. The first automated cleaning systems for high-rise building were used in Japan in the middle of the 80's. These systems were mainly designed for use on specific buildings. For safety purposes or in order to guide the robot's movement on the façade, they often required additional construction such as guidance rails to the façade.

During the last 10 years, there has also been a lot of effort towards the development of such façade cleaning systems in Europe. These systems, like the Japanese developments, were designed for specific buildings. The practical application of the systems mostly failed because of either a weak safety concept, poor cleaning quality, required additional construction to the façade, or simply due to expensive initial or operating costs. At this time, there is only one known system that is in practical operation. That is the automatic system for the cleaning of the vaulted glass hall of the Leipzig Trade Fair, Germany, which was developed by the Fraunhofer Institute IFF, Germany [4]. It must also

be added that this system is only applicable to this particular building.

Funded by the European Commission, a consortium formed by several European enterprises and research institutions is developing a semi-automatic low cost robotic system that is able to cope with the cleaning tasks of most of the existing large building façades.

This system is with minor changes adaptable to the largest possible number of buildings with homogeneously-designed façades. Additional constructions to the façade such as guide rails or scaffoldings are avoided or made unnecessary. The requirements for the control and sensor concepts are very specific, because the proposed robotic system is able to operate under adverse conditions such as changing weather conditions.

2 SPECIFICATIONS FOR A MARKETABLE ROBOT FOR FAÇADE CLEANING

To design a marketable and successful automatic façade cleaning system, it is necessary to provide a reliable, simple and economically efficient machine. The performance objectives may be summarized in:

- The total cost of the system must be under $ 75.000
- The system must be small (much less than 100cm x 80cm).
- The machine must master usual obstacles such as window frames
- One person must be able to handle the system
- Water and detergent must be recovered avoiding spilling
- Time to complete the cleaning of one square meter of flat glass façade should be less than 4 minutes.
- The system must be suitable for buildings with conventional installations

Many of the existing façade cleaning robots can only climb and clean completely flat glass window façades. However, most of existing buildings have homogeneously-designed façades but not completely flat. In many building there are not very complex obstacles, such as windows frames, that can be overcame by a not very sophisticated robot, allowing covering a very wide range of buildings with a single design.

3 CONCEPT OF THE ROBOTIC CLEANING SYSTEM

Existing façade cleaning robots are too complicated and/or too expensive to be introduced in the market. Moreover, most of these robots are not appropriate to cope with a wide range of façades, and those who have competitive costs are only able to clean completely flat glass surfaces.
All the high buildings use commercial carrier systems that support a gondola that moves on the façade for manual cleaning. One or two operators are needed for this task. Based in the existence of the carrier system on the building roof, the proposed robotic system uses it to reduce the costs of the vertical and horizontal movements. The system uses a commercial carrier with minor modifications for movements in axes X and Y (Figure 1).

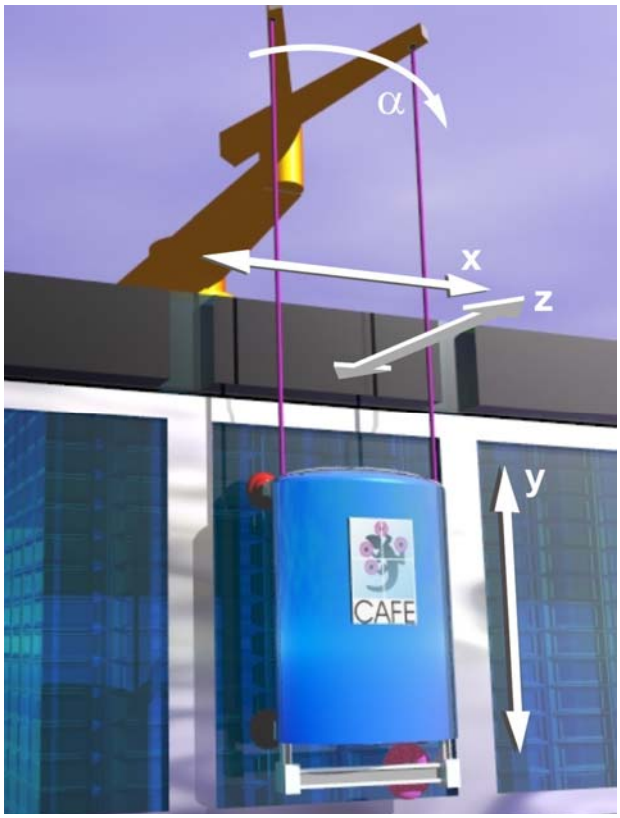

Figure 1. Façade cleaning robot concept

Completely autonomous systems result too expensive for the market and the proposed system has been designed to perform the cleaning task in a semi-automatic way. This means that many of the tasks will be performed in a completely autonomous way, however, because of security and economic considerations, a human operator will permanently control the robot operation.

The operator will be physically situated on the ground below the robot. In normal operation, he will be in charge of starting and stopping the robot action and changing the robot from one column of the façade to the following. It is not foreseen that the operator actuates during the cleaning of a façade column while in normal operation. He must only take actions in case of errors or emergency situations.

The robot cleaning system has been decomposed in four different modules (Figure 2):

- Cleaning Module (CLM)
- Kinematics Module (KM)
- Carrier Module (CaM)
- Control Module

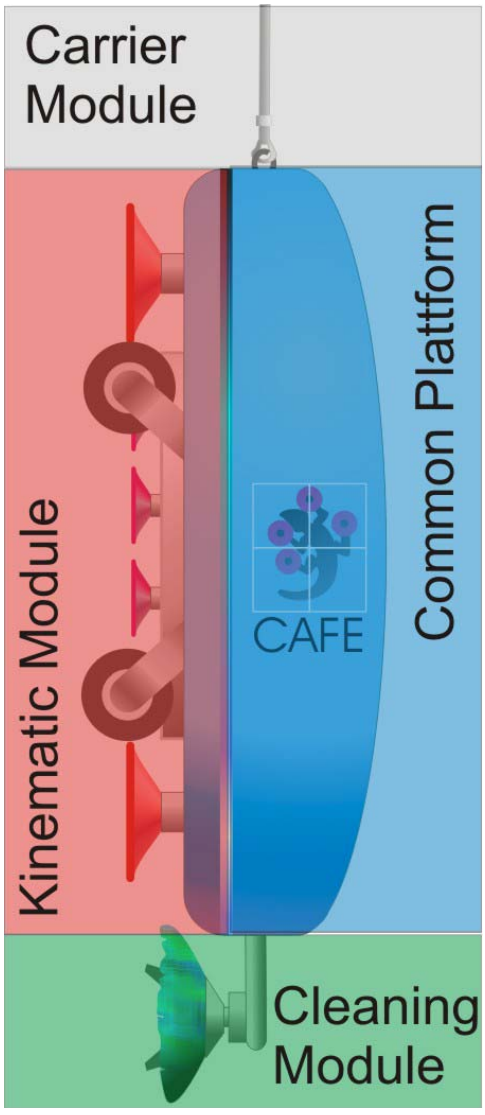

Figure 2. Arrangement and interconnections of the hardware modules

The Cleaning Module is in charge of the actual façade cleaning. It mainly consists in a cleaning mechanism and a positioning system. The façade cleaning mechanism is the part of the Cleaning module that is in contact with the façade and that mechanically carries out the task of cleaning. This mechanism is able to clean flat, glass surfaces and does not have the task of cleaning framework between glass panes. The cleaning is carried out using only water (little or no additives or cleaning agents) that is sprayed onto the glass. A brush that is in contact with the façade mainly forms the cleaning mechanism. This mechanism also has the task of sufficiently sealing off the area that is being cleaned, to ensure that the water used during cleaning does not drip down the façade during cleaning and, when necessary, so that it is possible to recover the used water for a water-recycling system. The quality of the seal is has been taken into consideration during the design phase and plays a large role in the cost of the system. The cleaning system is able to clean up to between 3-10mm away from a window pane. The cleaning head is shown in Figure 3 and the positioning system of the Cleaning Module is shown in Figure 4.

Figure 3. Cleaning head

The Carrier Module is responsible for moving and positioning of the cleaning system into the working position. This coarse positioning is realized by a vertical (Y), and horizontal (X) movement, as well as a movement in an orthogonal direction (Z) to the buildings surface for a coarse adjustment of distance between the cleaning head and the windows.

It is installed on the building rooftop and moves over rails or on a concrete path (guided along the parapet), holding and providing motion to the cleaning and

kinematics modules by means of cables. While the cleaning robot might be moved from one building to another, the carrier system will generally stay on the building rooftop.

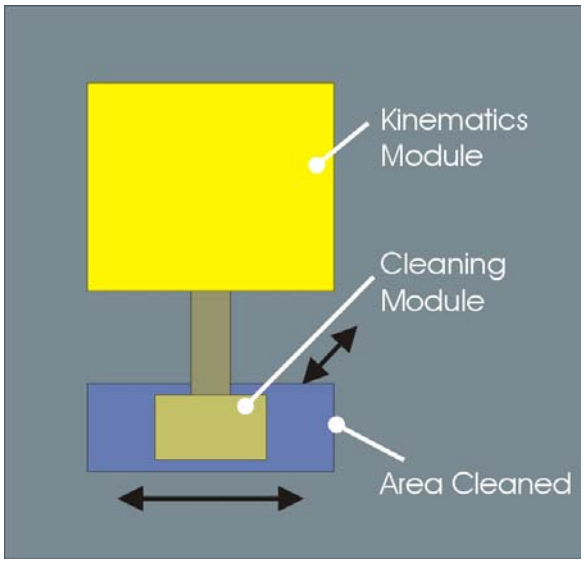

Figure 4. Positioning system of the Cleaning Module

The carrier must position the kinematics and cleaning modules on the façade at the beginning and between cleaning operations. The carrier positions the cleaning and kinematics modules in the X axis through its movement along the rooftop. The vertical motion and positioning in the Y axis is transmitted by the winding or unwinding of the cables. The adjustment of the distance to the wall Z is obtained by controlling the angle α (see Figure 1).

The carrier must also be able to bring the kinematics and cleaning modules down to the floor or hoist and deposit them on the rooftop in order to perform maintenance operations, refill cleaning water or even lay those on a vehicle on ground to be transported somewhere else.

Further the carrier is responsible for installation and supply of energy as well as other necessities for the Kinematics and Cleaning Module. There are not external wires and so, the Common Platform support wires are also in charge of the energy supply. This is done by introducing small wires inside the support wires.

The Kinematics Module establishes contact between the cleaning head and the window pane. This contact is necessary for generating a reaction force of the cleaning head against the window pane. The presence or absence of the contact is controlled by the system controller accordingly to nominal and non-nominal situations.

In nominal situations the contact must be established during the entire cleaning task and hoisting operation. The break of contact can induce serious problems like bumps towards the facade caused by oscillations of the carrier. In case of this non-nominal situation a safety module must be activated in order to avoid oscillations.

The role of the Kinematics Module is:

- To establish a stable contact with the facade.
- To keep the common platform apart from the facade surface at a constant distance (required for the cleaning).
- To follow vertical movement of the platform ensuring stable contact with the surface during the motion as well as during the cleaning (horizontal movement of cleaning module).
- To redirect platform in the surface plan (compensation for vertical motion deviations).
- To protect the facade and platform during lifting, i.e. during carrier movements, from possible damages (humps, caused by oscillations, wind etc.).

The term Control Module refers to the general architecture of the control systems of al the modules, and encompasses the concept for controlling each individual system.

The basic operation cycle is shown in Figure 5.

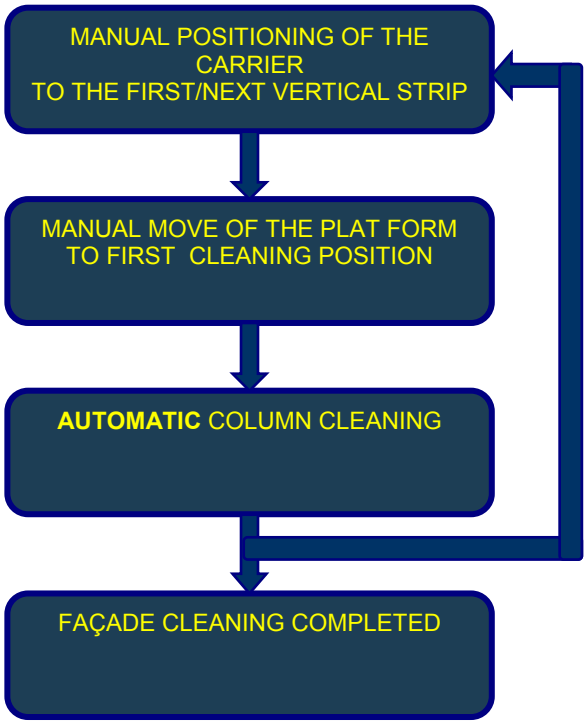

Figure 5. Basic operation cycle

4 CONTROL SCHEME

The cleaning task has been decomposed into different actions that must be performed simultaneously by the different robot modules. The control module is in charge of the synchronization of all this tasks (Figure 6).

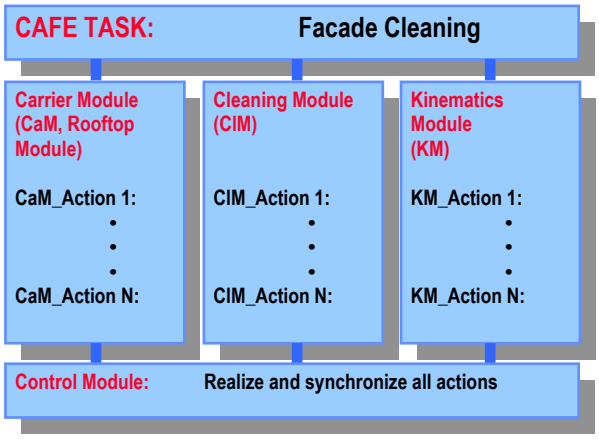

Figure 6. Decomposition of the cleaning tasks into modules/actions

It has been implemented a hardware decentralized and a software centralized control architecture, as appears in Figure 7. This architecture is considered more appropriate for the control system than a decentralized one.

This configuration reduces the total cost of the system and simplifies the integration.

The Control Module (physically located on the robotic Common Platform), the Carrier Module (for safety reasons) and the Operator Interface, include their own microprocessor based computer.

However, wire connection between the Control Module and the Carrier Module is not possible, while obviously the same happens between the Control Module and the Operator Interface. To solve this problem, a wireless communication (Ethernet WIFI 802.11b) has been established. The safety of this communication is critical and it has been guaranteed by a watchdog system. In case of failure of the wireless communication, all the system adopts a safety position and can be recovered manually from the Carrier Module Control. The communication scheme is shown in Figure 8.

The three modules physically located in the Common Platform (Control, Kinematics and Cleaning Module) communicate with each other either through a BUS connection with high-level commands. The lower-level processing of these commands is to take place within the individual module.

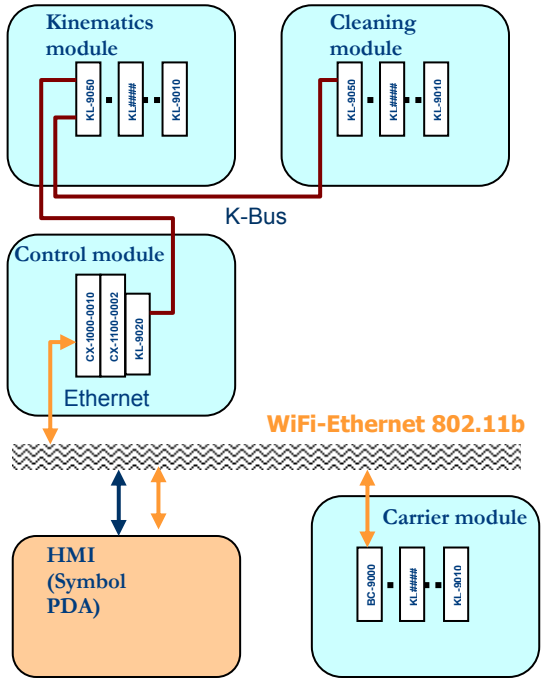

Figure 7. Control Architecture

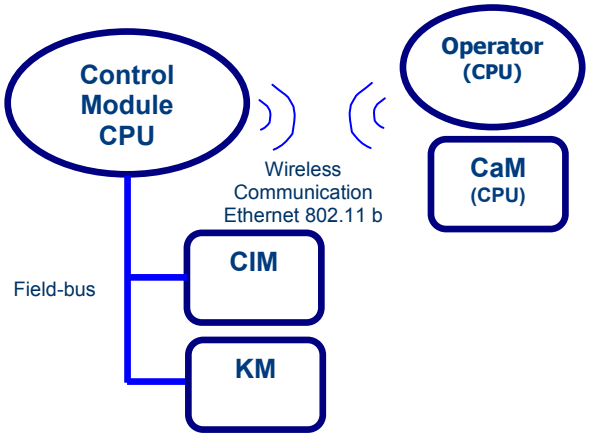

Figure 8. Communications between the modules

5 OPERATOR CONCEPT

There are mainly two options for the operator concept *Human-Machine Interface* (HMI):

- An advanced HMI based on a touch screen (probably with a PC with Win CE) and wireless communication

- A common HMI with buttons and interrupters

The first alternative will be more flexible and could result very intuitive. The cost is not very high and it will increase the complete system performance. Moreover, HMI based on touch screen will allow different control configurations and possible improvements of the machine in the future avoiding hardware modifications.

As it has been described above, wireless communication will be used between the HMI (operator) and the Control Module CPU that will be physically on board of the kinematics module. Currently, this communication is considered completely safe and the corresponding communication error safety system will be established to guarantee no damage, both the robot and the building, in case of fails in the communication. Other options are not appropriate because it will be very difficult to maintain a connection wire between the operator, on the ground, and the kinematics module, on the building façade.

Acknowledgments

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AN INSPECTION SYSTEM FOR DETECTION OF CRACKS ON THE CONCRETE STRUCTURES USING A MOBILE ROBOT

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Abstract: To assess safety, cracks in concrete structure are measured by inspectors, who observe cracks with their naked eyes and record them. But manual inspection is slow, and measured crack data is subjective. Therefore, this study proposes inspection system for measuring cracks in concrete structure and providing objective crack data to be used in safety assessment. The system consists of the mobile robot system and crack detecting system. The mobile robot system is controlled to keep a constant distance from the wall to acquire image data with a CCD camera on scanning along the wall. The crack detecting system extracts crack information from the acquired image using image processing. To improve accuracy of crack recognition, the geometric properties and patterns of cracks in a structure were applied to image processing. The proposed system was verified with experiments in both laboratory environment and field.

Keywords: crack, inspection, image processing, mobile robot

1 INTRODUCTION

Over the last several decades, many concrete structures have been constructed on a variety of the fields. Concerns have been directed towards the safety of concrete structure. To determine safety in this structure, periodic inspections have been conducted using non - destructive testing technologies and techniques. Non-destructive tests, however, cannot replace the human visual inspections because they entail their slow and complicated procedures. For this reason, Non-destructive tests have been limited to precision inspections [1]. In the first stage of inspection, cracks in the concrete structure are usually measured by inspectors who observe cracks with their naked eyes and record them while walking along the structure. As such, the main disadvantage of visual inspection is the impossibility of making a fast and sure survey.

Therefore, varied studies developments of automatic crack inspections using image processing have been made in areas including roads, bridges, fatigues, and sewer-pipes[2]-[5].

The Komatsu Engineering Company has developed and commercialized an image acquisition system that can acquire the images of road and tunnel lining by using a laser-scanning device [6]. The Railway Technical Research Institute in Japan developed an image acquisition system of railway tunnel lining by using line CCD cameras. Roadware Group Inc., Canada commercialized a system that acquires an image of the road with a CCD camera, an ultrasonic sensor, and a gyro-sensor with a speed of 80km/h and a resolution of 3~4cm [7]. Those systems are useful to collect data of cracks, leakage, scale, and spall but only by using the image acquisition, and not through automatic defect detection. The algorithm for crack detection and measurement is required for fully automatic inspection system. It is necessary, therefore, to develop the automatic crack detection and measurement algorithm to obtain both fast inspection and objective crack data.

Cameras and lasers are widely used to image the surface for inspections of the surface of structures. Although it is sufficiently efficient to be applied in a wide variety of fields, the laser-scanning device is too costly and it has a heat problem in maintaining the system. The camera-scanning device is more cost-effective than the laser device, but it still has an illumination problem. It is common sense in engineering that cost is one of the most important considerations. Study of the image data acquisition of the surface acquired by cameras is therefore necessary to ensure a high level of safety in the concrete structure.

Therefore, this study proposes an inspection system for cracks on the surfaces of concrete structures that inspects faster and more objectively than the manual inspection. The inspection system is consisted of a mobile system and crack detecting system. The mobile robot system is controlled to keep a constant distance from the wall to acquire image data with a line CCD camera on scanning along the wall without inspectors. To obtain fine images, a high power illuminator, shock absorber devices and a sensor for measuring velocity for control the line CCD camera are used. The maximum inspection speed of the system is 5km/h when the resolution is set to

0.3mm/pixel. The crack detecting system is software that extracts crack information through image processing from the acquired images. Measured crack information is composed of crack thickness, crack length, crack orientation. They are important factors for the fundamental inspection. To test the proposed system, experiments were performed inside the buildings and road tunnels

2. THE DESCRIPTION OF THE INSPECTION SYSTEM

2.1 The subject of inspection

An itemized list of contents of the inspection of concrete structure contains cracks, leakage and spall etc. In an itemized list, the survey on cracks is very important factor to be determined safety in evaluating the concrete state [8].

Cracks in the concrete structure are the combined results from deficiency in the repairing period, the contraction due to a plunge in temperature, fluctuation between contraction and expansion caused by the temperature change, extra loads from the partial ground expansion.

The cracks are categorized as vertical, horizontal, shearing and complex crack. The proportions of the categories are 40% vertical, 11%horizontal and 30% shearing [9]. Therefore, the proposed system is targeted to inspect vertical, horizontal, and shearing cracks.

2.2 The system configuration

The crack inspection system consists of mobile robot system and crack detecting system as shown in Figure. 1. The mobile robot system is composed of optical, mechanical, and data storage devices that obtain the image of the inner face of the concrete structure to maximize to contrast distribution of crack and non-crack and minimize the noise while it moves parallel to the structure.

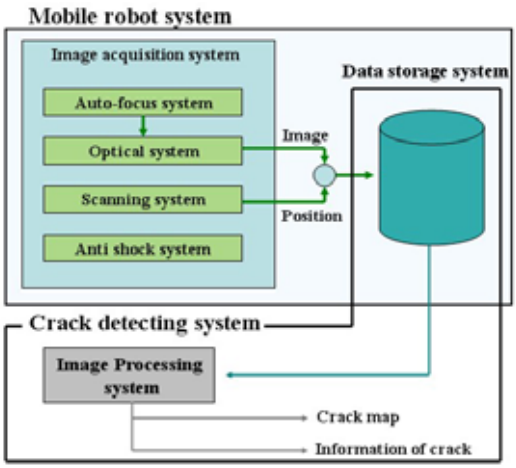


Figure 1. Schematic Diagram of Inspection System

The crack detecting system is software that extracts and computes the numerical information of cracks from the image data.

The information, including length, width, and orientation of the cracks gives a clue to judge and determine the next stage of precision inspection of concrete structuer safety.

The mobile robot system consists of a CCD camera, frame grabber, controlling apparatus for an autofocus device, isolated vibration device, illuminator, encoders to measure moving velocity and to compute the distance from the structure for an autofocus, and a computer for controlling the system. Figure 2 shows the image acquisition system.

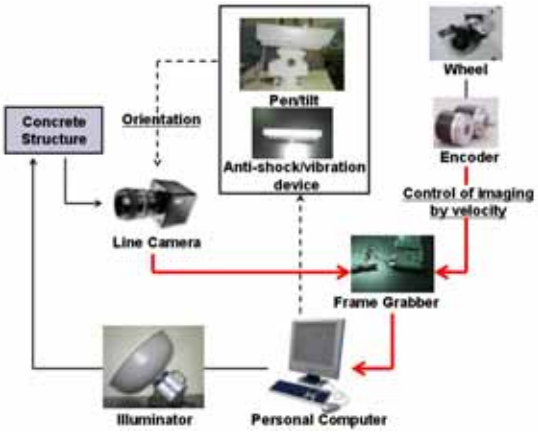


Figure 2. Mobile Robot System

CCD cameras are either line-scan or matrix cameras, based on their array of light sensitive devices. The main advantages of the matrix camera are that the camera takes images of an area with one exposure so it is similar to the human eye and the interface of the camera is standardized. However, it is difficult to obtain images over a large area due to the low density of sensitive devices. It is hard to take a photograph with a line-scan camera because there is only one column in the array of a light sensitive device. This means that, for the photograph, the object or camera must move one direction, but it has the advantage of being able to image a large area because of the high density of the sensitive device. The proposed system, therefore, imports a line-scan camera for the image acquisition sensor.

If the camera does not move with constant velocity while it takes images from the surface of an object, the size of scanned-images changes in correspondence to the different velocity.

For this reason, the control of line-rate on the line-scan camera could be accomplished through feedback of measured velocity. So, the line-rate of the camera can be controlled by TTL level pulse with an encoder.

The line-scan camera usually requires a high power illuminator. A maximum 1000W halogen light is selected for the mobile robot system.

To obtain fine images from the camera, the mobile robot have to keep a constant distance from the structure that is not straight path but changed path continuously. The mobile robot system, therefore, has a laser sensor that obtain the distance and the angle between mobile robot and concrete structure and has an autofocus device for depth of the field using the obtained distance.

The system is 0.3mm/pixel when the distance between the surface and the camera is 1.5m.

3. SYSTEM CHARACTERIZATION

3.1 Mobile robot system

The wheels of the mobile robot have the subject of formation made by the speed difference of two wheels controlled by two auto actuators. The diagram to realize the kinematical model is set as the following Figure 3.

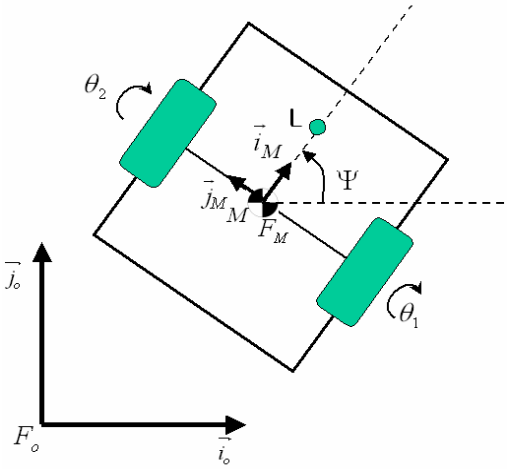


Figure 3. Schematic Diagram of Mobile robot

Figure 3 is the model of mobile robot that has two driving wheels. In the diagram, M is the standard point as the CG point of the robot. O is the origin point of the standard coordinate, and M is the origin point of the coordinate of the robot. In order to obtain the simple kinematical model, the wheels of the robot are presumed to satisfy the complete rolling requirement on the surface without the sliding on the side. Through this hypothesis, the following kinematical formula may be obtained.

$$\begin{aligned} \dot{x}_M &= \frac{r}{2}\left(\dot{\theta}_1 + \dot{\theta}_2\right)\cos\Psi \\ \dot{y}_M &= \frac{r}{2}\left(\dot{\theta}_1 + \dot{\theta}_2\right)\sin\Psi \\ \dot{\Psi}_M &= \frac{r}{2}\left(\dot{\theta}_1 - \dot{\theta}_2\right) \end{aligned} \tag{1}$$

Eq. (1) is the kinematical function of the most generalized two-wheel driven robot. However, the first two formulas have the nonholonomic feature that cannot completely be integrated that it is difficult to control. First, the point that is connected in imagination is presumed to apart with the distance of d from the axis of the wheels. In the event that the control position, namely, d=0, is set in the middle of the robot, it is not collected accurately on 0. However, in the event that d is not 0, namely, the origin point is set in a place apart by d from the robot axis, it is collected on 0. Therefore, d has to be set near to the center of the robot and control.

3.2 Automatic crack detecting

The crack and the surface can be distinguished by the the contrasting light reflection. The analysis system is composed of a crack detection and measurement algorithm that utilizes the images derived from this pattern of reflection. The current use of automation by image processing is limited because the complete realization of automation is hard to achieve in an unpredictable environment. Although this study has the goal of complete crack detection, it is not easily accomplished. Therefore, the semi-automatic algo-rithm is realized.

If the images contain high contrast between cracks and the background, crack detection can be performed efficiently even though the illuminator is not completely stable. The histogram equalization defined by the following Eq. (2) is methods for enhancing the contrast of an image.

$$s_k = \sum_{j=0}^{k} \frac{n_j}{n} \qquad k = 0,1,2,...,L-1 \tag{2}$$

Where

s_k : Acquired normalized gray-level value

n : Number of pixel

n_j : Number of pixel that has j gray-level value

k : The input gray-level,

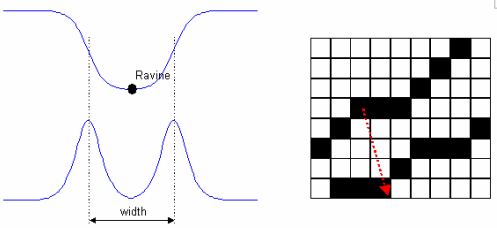
To extract crack information, the edge of the crack has to be extracted and the Sobel and the Laplacian operators are applied. The Sobel operator is applied to obtain the orientation of the edge as shown in Eq. (3) [10].

$$\phi = a\tan 2\left(\frac{\partial f}{\partial y}, \quad \frac{\partial f}{\partial y}\right) \tag{3}$$

To find the zero-crossing point from the second derivative is easier and more efficient than to find the maximum point from the first derivative. Also The Laplacian operator has rotation invariant property and the acquired edges are closed curve line that is an advantage of this study targeting a region composition from the crack edge. To get the stiff second

derivative Gaussian filter is applied because the Laplacian is sensitive to noise.

The detected edge constructs a ravine, which is defined as a local minimum point between two edges as displayed in Figure 4(a). The 2-D image is scanned in the direction of edge as seen in (b) and the 1-D profile is acquired as in (a).



(a) (b)

Figure 4. (a)1-D profile of ravine
(b)2-D profile of ravine

The scanning from one edge to the other is stopped when it satisfied with follow condition.

In the first place, when the scanning cross the other edge, the position of local minimum point is acquired and stored, and then the width of the crack from the minimum point to the edge is calculated. In the second place, when the current pixel gray-level is higher than that of edge. Finally, when the scanned length is longer than threshold, it gives the high efficiency of calculation and the effect of noise removal because the crack is lengthy but it has problem that can not detection thick cracks which is thicker than the threshold.

The area extracted from images should be grouped according to the pattern of connection. A specific crack implies the set of pixel, and in this paper, the depth first search method was implemented in order to label each region [11].

The discontinuous image may decrease the connectivity within pixels. This further makes influence on the calculation of features by labeling differently even in the same region. To solve this problem, slopes of each segment end are computed with certain number of pixels being modeled into a straight line, and the segments are merged if the gradient change is miniscule between the segments.

3.3 Crack extraction via graph search

With a given start point and an end point, a graph is constructed by images and the boundary of the image is estimated through finding the least cost function. The pixels of an image are interpreted as nodes and 8-neighborhood of a pixel are connected via links in the graph, using Dijkstra method for finding shortest path [12].

① Input all nodes from the expansion of the start node into the queue. The previous node pointer is defined as nA. Calculate the cost of expanded nodes.

② It is failure if the queue is empty. Output the least cost note ni from the queue and remove it. If $ni = nb$, back-track the previous pointer saved in each node and terminate.

③ If the condition to terminate in the process ② is not satisfied, expand the node ni and input all other following nodes into the queue. Define the previous node pointer as ni and calculate each cost of node. Go back to the process ②.

This algorithm always finds an optimal value. How-ever, the number of enlarged nodes is numerous. To correct the inefficiency, a method that does not require the expansion of a node if the cost per unit length is above a certain value is used. Figure 5 shows the algorithm.

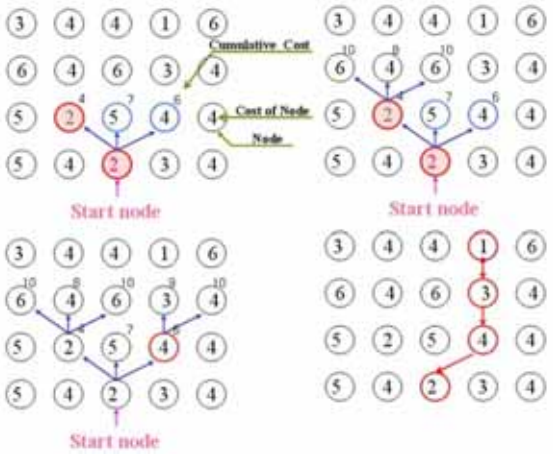


Figure 5. Example of Dijkstra method

3.4 Crack measurement

Not all prospect crack area is derived from cracks. The causal elements include construction layer, an artificial mark, noise, or blot. So, this erroneous area is removed when it is satisfied that a very small area resulted from noise and an area whose shape is not long and narrow is not a crack and very straight area resulted from the attachments such as construction layer or a cable.

This paper uses the quantum for the crack length, width, and the direction. The width of points comprising each area is already calculated when the region is formed from the edge. To remove the outlier among these, the width was derived as a mean value using 5 lengths of median filter. The width of each area is calculated as Eq. (4).

$$w = \frac{1}{N}\sum_{i=1}^{N} \hat{w}_i, \quad \hat{w}_j = med\{w_{j-2}, L, w_{j+2}\} \tag{4}$$

Length depends on the number of pixel. After calculating the length of diagonal as $\sqrt{2}$, and the vertical and horizontal line as 1, the real length was measured by the camera calibration

4. EXPERIMENT SETUP AND RESULT

4.1 Experiment setup

In an experiment at an indoor structure, the image of the surface wall was obtained by mobile robot that could keep a constant distance from the wall and an encoder on its wheel. Even if mobile robot can't keep a constant distance, using the laser sensor, the image of the surface wall was obtained by adjusting focus ring. To prevent the vibration transmitted to the camera by a disproportionate state of the floor, the flat board upholding the camera was stabilized by a wire rope. Figure 6 shows the experiment setup for indoor circumstance.

Figure 6.Experimental setup in a building.

Figure 7 displays the image processing software. The crack information is released from the right side of the software. Figure 8(a) is the menu offered for camera calibration, inputted through a conversion of the distance between each pixel into mm. The camera calibration used the plate which has the black dot on the surface with an interval of 5mm between each point. Figure 8(b) shows an over-layered image of both obtained image and extracted compensating points.

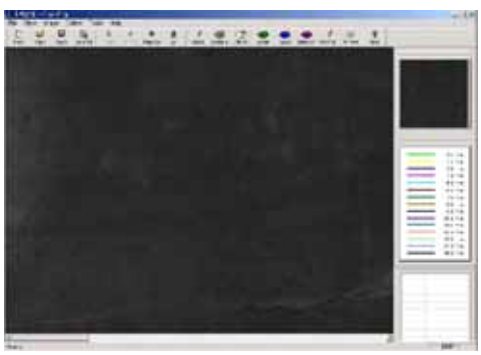


Figure 7. The software of crack detecting system

(a) (b)

Figure 8. (a) Window for mapping data
(b) Over-layed Image for clibration

*4.1 Experiment result*t

The image acquisition from the indoor structure was seen in Figure 9 and the crack detection was extracted as shown in Figure 10. The two vertical lines on the right of circle is groove embedded in the structure. Therefore, the highly straight line was removed, following the recognition.

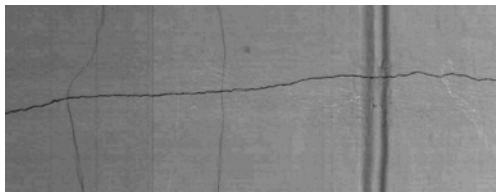


Figure 9. Image of indoor wall

Figure 10. Extracted crack of indoor wall

Figure 11 and Figure 12 exhibit the process and the result of acquired image. Since the finishing line of iron bar was not longish and formed a certain area instead, it was not recognized as crack.

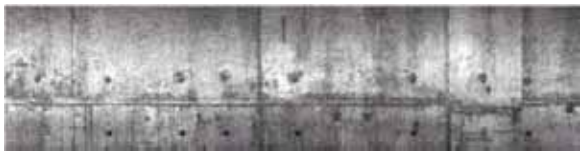


Figure 11. Image of subway inner wall

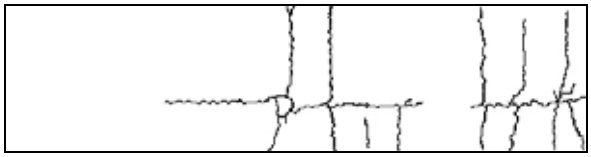


Figure 12. Extracted crack of subway inner wall

Above process result was shown as a picture in order to discriminate by human eyes. The crack orientation displays vertical, horizontal, and diagonal crack, using length, width, the start point and the end point.

The crack inspection system proposed in this paper, although the state of surrounding environment is not negligible, has overall error rates of 75~85% and the measuring error of recognized crack is 10% or less.

5. CONCLUSION

This paper proposed an inspection system using an image process, which can be a solution to the problems of crack detection in concrete structuer, slow rate, subjectivity, and the inefficiency in managing data. Also, the system ensures the validity and possibility based on the experiment in the indoor structure, road tunnel, and subway tunnel. However, an erroneous recognition of a crack as non-crack and vice versa prevails. Therefore, the system is semi-automated to get rid of wrong recognition of non-crack as crack, and to identify crack by a graph search method using the user-based input of the start-point and end-point of crack.

In order for a crack inspection system to develop in to an expert system, there needs to be further study of the characteristics of cracks and the algorithm must move towards complete automation. It is hoped that this paper will encourage futuer research.

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Prioritization System for Building Maintenance Applications in Public Universities

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Abstract: This research present a system named Prioritization System (PS) to support the maintenance engineers while they are making the decision about the priorities for maintenance applications of school buildings. Distinguished from the other research done before, which built the priority model only with historical data, the PS presented in this research bases both on historical data and knowledge, which is deposited in a school maintenance knowledge base. The standard estimation criteria and electronic medicine documents of buildings are set into the PS, which will be integrated with a School Building Maintenance System (SBMS). Automatically prioritized by the system according to the estimation criteria could avoid mis-determining subjectively made by people themselves. Besides, the system enhances its decision support and reduces the replacement cost for management jobs.

Keywords: Prioritization System, Maintenance, School Building, Knowledge Base, University

1. Introduction

School buildings are not only a major group of public buildings, but also the largest essential hardware in development plans for schools. Therefore, the role that procedures of school building maintenance play in school administration is getting more and more important while the education development is promoted. There are more than one hundred and fifty colleges/universities in Taiwan; sixty percent of them are more than twenty years aged. The aging problems of buildings are appearing and the maintenance applications are increasing. No matter how many maintenance requirements increased, the unchangeable fact is that the maintenance budget is limited. Consequently, how to keep maintenance quality is becoming a stronger challenge than before. The main issue discussed in this research is how to make use of information technology to provide a platform with objective and standard estimation criteria for prioritization of school building maintenance. The main objects of this research are public universities in Taiwan. After literature survey, field survey, and questionnaire survey, the research schemed out an index architecture. Under the framework of a management system of school buildings, the documentation knowledge are used together with to knowledge in multi-media objects to reason out health states of school buildings. After that, the system will produce the maintenance priority automatically through the reasoning of estimation rules. This estimation system for maintenance prioritization is built to reduce the workload of routine jobs for maintenance engineers and avoid negative influences for school building management, such as improper allocations of limited maintenance resources, possible endangering of public safety, accelerated deterioration of building health, or obstacles of entire school development.

Compared to the Bridge Management System, which has been developed in Taiwan, Japan, and U.S.A., the elements consisted of the Building Maintenance System are more complicated. However, development of the Building Maintenance System in Taiwan is still insufficient. Take the sixty public universities of Taiwan as examples, only twenty-two percent of them have built relative maintenance management systems. The functions of these systems are simply applying and querying. That is one of the most important reasons that the PS could not be built into a complete Building Maintenance System and verify its effects on prioritization support. That is also the major limitation of this research.

2. DISCUSSION ON PRIORITY MANAGEMENT AND COMPUTING

For a long time, either public or private institutions paid much more attention to constructing than to maintenance. Not only the ignored attitude but also short of budget and resource are reasons for neglect of maintenance [1]. Limited maintenance budget accompany with limitless maintenance requirements is the fact that administrators of universities are forced to face. Therefore, through the support from a knowledge base (KB) to prioritize required

maintenance of school buildings could bring the higher efficiency for usage of limited resources. Currently, there are few research on building maintenance prioritization, and most of them discussed about maintenance prioritization and hazard determination of dams, bridges and road pavement, but not of buildings. Regarding the buildings, Al-Majed presented a set of standard estimation criteria of public building maintenance in 1998. He divided twenty-three factors into two dimensions, management and execution [2]. In this research, the architecture of the PS is based on an estimation benchmark of school building maintenance proposed by Chang Chih-yuan in 2004. In his research, the estimation benchmark of prioritization is composed of sixteen factors, which are grouped into three dimensions included urgency, health and economy. To avoid subjective estimation, he merged applicants' and engineers' feelings into consideration when he designed the estimation factors [3].

Via questionnaire survey, the research discovers that almost all public universities in Taiwan have no standard estimation criteria, except few military colleges or universities. However, the professed standard estimation criteria of the military colleges/universities are made by few people subjectively, and not produced by scientific research methods. Besides, their purposes are to determine importance of essential military facilitates. At present, there are only thirteen universities have related maintenance management systems. And functions of these systems for end users are only applying and querying. Besides that, from the functions of the systems, which are provided to the end users, we can find that only National Taiwan University of Arts has considered building a KB about construction, but no related maintenance management system has been concerned. Through questionnaire survey, this research found that there is no other public universities in Taiwan reveal any consideration of using KB to support maintenance prioritization. (See Table1)

Table1. Maintenance Management Systems of public universities in Taiwan.

Universities		Main System	Prioritization Using of KB
01	National Chengchi Uni.	On-line repair applying system.	×/×
02	National Chiao Tung Uni.	Construction works applying/querying system	×/×
03	National Central Uni.	On-line repair/maintain system.	×/×
04	National Taiwan Ocean Uni.	Repair/maintain service system.	×/×
05	National Ilan Uni.	School building repair booking system.	×/×
06	National Changhua Uni. of Education	Dormitory repair booking system.	×/×
07	National Sun Yat-sen Uni.	Repair booking system.	×/×
08	National Kaohsiung Normal Uni.	Repair/maintain booking /progress report system	×/×
09	National Uni. of Kaohsiung	Repair booking system.	×/×
10	National Kaohsiung First Uni. of Science and Technology	On-line repair applying system.	×/×
11	National Pingtung Uni. of Science and Technology	Repair/maintain service system.	×/×
12	National Tainan Teachers College	School building repair/maintain service system.	×/×
13	National Taipei College of Nursing	Repair booking system.	×/×

In the final report of plans for knowledge management of construction industry, which are instructed by Construction and Planning Agency of Ministry of Interior (CPA), the knowledge management of construction industry has been well planed[4], but there is no detailed illustration about how to implement and execute practically, not to mention the plans of making use of knowledge management in educational institutions and real maintenance jobs. In Mohamed's research, 1996, he has built a network optimization model into a Bridge Management System to control two major types of activities in bridge management works. Besides, the more important is that he used the model to figure out the best resolution for execution time and resource allocation of maintenance jobs [5]. As to Ramadhan's research in 1998, effective factors and a predictable model are brought up for a road pavement management system. He built the model by gathering information from experts and the past experiences to prioritize the importance of the road sections that required maintenance [6]. However, the model is built based on the historical information and how to keep its effectiveness and accuracy is a big challenge. Most maintenance management system nowadays tend to provide maintenance flow control and execution, but how to use tacit knowledge hided in brains of maintenance engineers or in maintenance organizations to support management jobs are not been much concerned. 2004, C.Y. Chang presented Anthropopathy Health Efficiency Indicators of Building Management（AHEI）= Gi (Geographic Climate) *(X_1E（Regular Effects）+ X_2Q（Ratio of Quality Depreciation after Building）+ X_3M（Ratio of Annual Maintenance after Building）) in his research on

Anthropopathy Health Efficiency Indicators of Building Management[7]. The formula of maintenance factors may deposit in the PS to offer the system a standard for priorities determining, in order to avoid misadvising because of subjective recognition.

3. PS APPLICATION IN SCHOOL BUILDINGS

This research intends build a system to estimate the priorities of school building maintenance. For this reason, the system is designed mainly from the views of maintenance engineers and administrators in universities. The three main roles included in the system are inspectors, managers and maintenance staff; inspectors are responsible for building inspecting (generally served by school maintenance engineers or outsourcing professionals); managers are in charge of and make use of buildings; maintenance staff performs and manage maintenance works. The system divided all school into different areas depending on particular use units, and then analyzed health states of each building. In each building, there are many different maintenance types, such as construction, water and electricity, decoration, and so on. Each maintenance type consisted of various items, such as construction patching, pipes and wires replacement, wall covering, and so on. The PS estimates the priority for each item according to its weight of ranking, degree of measurement and knowledge from KB.

In this paragraph, the essential operations in the framework of the system will be described in Section 3.1. Section 3.2 will illustrate the base of the PS, which is the content of school building maintenance KB and its operation methods. The last section 3.3 is going to discuss operation situations performed by three main roles of the system.

3.1 Prioritization System

The PS may be considered as a subsystem under the architecture of the School Building Management System basically (See Figure1). It is performed in two ways, an active way and a passive way. In active way, the system reasons automatically with rules of KB according to electronic medicine documents of buildings and inspecting results to comprehend the health states of buildings. In passive way, the system gets information of present condition of maintenance items from user interfaces when the maintenance cases are applied. After the cases are applied, the system will check experiences of the past cases, refer to their health states, and then reason with rules to decide priorities. One distinguishing feature of this operation model is that the system will record the health states of each building into their electronic medicine documents. The electronic medicine documents of building contain default information of the buildings, since they have been built up, and the following maintenance histories. No matter in active or passive way, the system could consult the electronic medicine documents to get health states of buildings as bases of estimation.

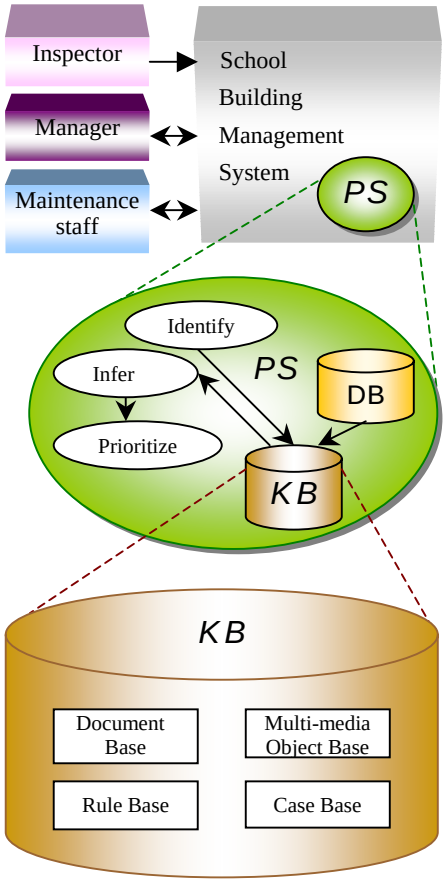

Figure1 Piroritization System

3.2 Maintenance Knowledge Base

Maintenance requirement does not cease. Every maintenance item has symptom cycles. The same symptoms may appear repeatedly in different buildings. However, such information and knowledge keep in brains of maintenance staff. Users of buildings have no idea about that and could not learn how to use the facilities correctly and maintain them carefully everyday without learning from the past experience. Therefore, the users are used to raising maintenance applications immediately whenever a single tiny symptom of damage appears. Incorrect customs of using facilities and neglectful attitudes to maintenance resources not only increase burdens to maintenance engineers, but also waste budget and resources. For this reason, this research presented the PS based on the KB to induce health states, case histories, estimation criteria and measure rules to become structural knowledge and deposit in the KB

for referring when maintenance jobs proceed. Knowledge in the KB could also be the educational or training resources referred by maintenance staff to guide users of school buildings. With accumulated knowledge, frequency of improper usage and replacement cost of management could be reduced down by the system.

Regarding utilities of KB to support maintenance management, although J. de Brito et al. presented a prototype of an expert to help decosion-making for concrete bridge management, the contents of the knowledge base they used are not particularly discussed [8]. Duing to difficulty in solving unstructural and complex problems with rule-based knowledge, Heng Li used the accumulated experience knowledge of past cases to solve the unstructural and complex problems, such as negotiation problems [9]. However, compared with concrete bridges, buildings consisted of more various elements, which made considerations of decision-making more complicated. Besides utilization of the past cases for diagnosing diseases of buildings, the usage of rule-based knowledge, in order to infer for the best maintenance priority, is also necessary. Therefore, the KB proposed in this research integrated various important kinds of knowledge about school buildings. It contains four knowledge depositors, the document base, the rule base, the multi-media object base and the case base. As Figure 2 displays, knowledge of each depositor is illustrated as followings:

1) The Document Base：deposits related laws, regulations, or stipulations, case or research reports, and forms or lists for school administration procedures, in order to be referred by users and maintenance staff when they proceed maintenance jobs.
2) The Rule Base：deposits estimation criteria and measurement rules of maintenance prioritization, in order to be referred by the system when it prioritize maintenance items.
3) The Multi-media Object Base：deposits building symptoms with multi-media object, in order to be referred by maintenance staff when they would like to know the states of building in remote and to reduced the cost of management.
4) The Case Base：deposits experiences of the past cases, and then integrates them into electronic medicine documents of buildings, in order to be the basic adjustment resources of measurement rules for maintenance estimation.

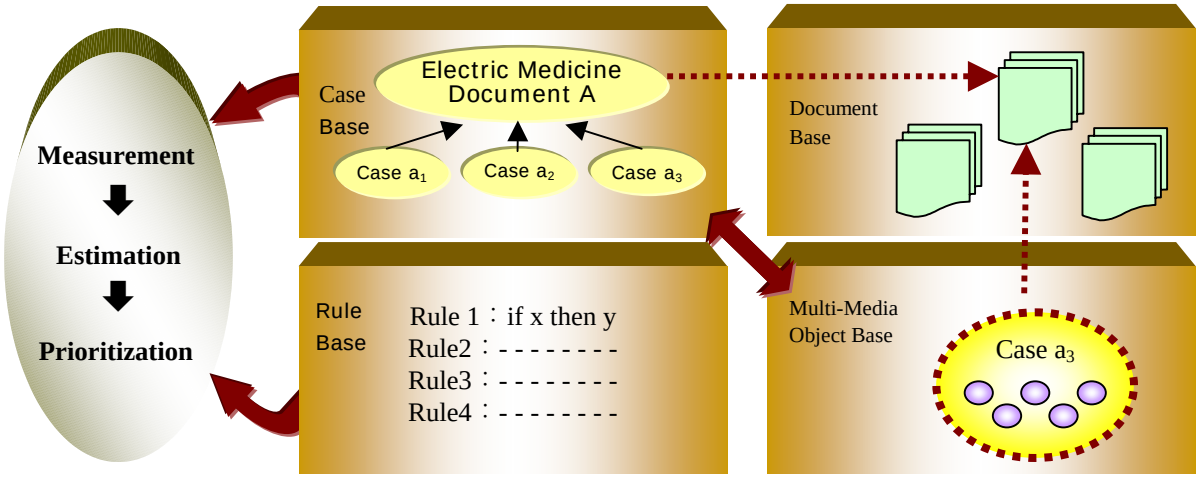

Figure 2 Knowledge Base of PS

The default information of an electronic medicine document is the basic data of a building, which were set when it was built. The following maintenance states will modify the related parameters in the electronic medicine document of the individual maintenance item and then produce a real document into the document base. States of buildings or items in case base may be indexed according to their superiors and deposited in multi-media object forms. When the cases are referred to, their related multi-media objects will also be provided by the system automatically. Maintenance staff could get information about states of building or maintenance items. According to the health histories of the buildings, the system could determine maintenance priorities after it reasoned with estimation criteria and measurement rules.

3.3 PS Operations

There are three main types of the system users, which are inclusive of inspectors, managers and maintenance staff. The different operational situations for these three main roles are described as followings:

1) Inspectors: inspect buildings routinely and accidentally. The inspected information of building states will save return to the system, in order to modify the electronic medicine documents of the

buildings, and the system will then transfer it into the document base.

2) Managers: are graded into two levels. The first level is indicated building manager, and the second level is partial building manager. Two levels have been delegated different authorities. Partial building managers are people who have right to use the buildings, but indicated building managers are not only the building users, they are also persons in charge of the entire buildings. Both levels have right to raise maintenance applications, when necessary, with multi-media object attached. The system will find the similar cases for referring to reduce inconvenience in waiting time of the maintain procedures.
3) Maintenance staff: will be assisted by the system with related documents or regulations searched with keywords, in order to comprehend the maintenance progress and matters that need their attention. In the meanwhile, the system gets the medical documents of buildings from case base and prioritizes the maintenance items based on the information obtained from the user interfaces of the system and estimation criteria obtained from the rule base to support the staff.

To enhance effectiveness and accuracy of health histories which are referred when prioritizing, the system deposits each maintenance case into case base for updating health states of buildings and accumulating the relative experience knowledge. Besides, maintenance managers get decision support for maintenance jobs through user interfaces, which are provided by the system according to the documents, regulations, case experience and multi-media objects of the KB.

4. CONCLUSION AND SUSSESTION

The priority index architecture presented in this research is results, which is analyzed from the professional opinions of the maintenance authorities in sixty public universities in Taiwan and could be standard estimation architecture for maintenance prioritization of school buildings. The PS is differed from other related systems, it emphasizes that the estimation based on the KB could assist maintenance staff to avoid improper resource allocation caused from misdetermining. Interoperations of various types of knowledge strengthen effectiveness and accuracy of maintenance prioritization. For example, when the system estimates priorities with standard criteria of rule base, it also refers to the electronic medicine documents, in order to assure that the decision is made while the health states of buildings are quite well comprehended and the opinions of building managers are considered. It could also avoid determining in biased views and causing damages of buildings and danger of people lives because of neglecting of real health states of buildings. The PS based on the KB determines maintenance priorities under the support of maintenance knowledge automatically. It helps the decisions to be made objectively and promptly, to reduce workload of maintenance staff of universities, and to promote quality and effectiveness of maintenance jobs. By accumulated knowledge, the system could enhance its decision support to maintenance management jobs and decrease cost of management replacement.

After the literature survey, the interview with professionals, and field survey, this research found that research both on index architecture of building maintenance prioritization and implementation of maintenance knowledge base are in the beginning in Taiwan. The objects of this research are buildings of public universities of Taiwan. There are only thirteen universities have related building maintenance systems and the functions they offered are simply applying and querying. Therefore, this research could only propose design and develop suggestions for the initial model of the current integration or the system blueprint for the future plans. Regarding testing effectiveness of the system, real experiments have to wait till the complete SBMS is built in few years. Besides, as to operations of KB, the future researches could try to increase its searching efficiency of document base or case base. For example, to make use of the Ant Algorithm to classify the cases first for speeding its searching, to compare speed of keywords searching with that of ontology searching, or to mobilize the system.

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THE DEVELOPMENT OF A MACHINE VISION ASSISTED, TELEOPERATED PAVEMENT CRACK SEALER

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ABSTRACT: Crack sealing is a maintenance technique commonly used to prevent water and debris penetration and reduce future degradation in pavement. The conventional crack sealing operations are, however, dangerous, costly and labor-intensive. Labor turnover and training are also increasing problems related to crack sealing crews. Automating crack sealing will improve productivity and quality, and offer safety benefits by getting workers off the road. The reduction in crew size and the increase in productivity of the automated sealing process will be translated directly into significant potential cost savings. The main objective of this study is to develop an automated system for sealing cracks in pavement, and to validate the developed system through field trials. A machine vision algorithm, which is composed of noise elimination, crack network mapping and modeling, and path planning, was developed to operate the proposed automated system effectively. Extension of the algorithms and tools presented in the study to other applications is also recommended for future studies.

KEYWORDS: Crack sealing, Pavement, Automation, Machine Vision, Path Planning

1. INTRODUCTION

Aging of our pavements is most visibly exhibited in the form of surface cracking. Surface cracking in pavements should be repaired because it increases pavement degradation, which can lead to the significant reduction of the service life of a pavement. If cracks in pavements are not sealed, surface water penetration can reduce the strength of the sub-base layers, which might result in broader cracks and potholes. Among various methods for repairing cracks in the pavement, crack sealing is an effective strategy utilized by maintenance authorities around the country. The conventional crack repair method is, however, dangerous, costly, and labor-intensive. Labor turnover and training are increasing problems related to crack sealing crews.

Automating pavement crack sealing process will improve productivity and quality, and will offer safety benefits by getting workers off the road. The reduction in crew size and the increase in productivity of the sealing process will also be translated directly into significant potential cost savings. Since 1990, several systems for automatically sealing surface cracks have been developed in highway construction and maintenance area. The primary objective of this study is to: 1) develop an Automated Pavement Crack Sealer(APCS), 2) briefly illustrate a machine vision algorithm developed for mapping and modeling the exact locations of pavement cracks to be sealed, including path planning, and 3) validate the technical feasibility of the APCS through several laboratory and field tests.

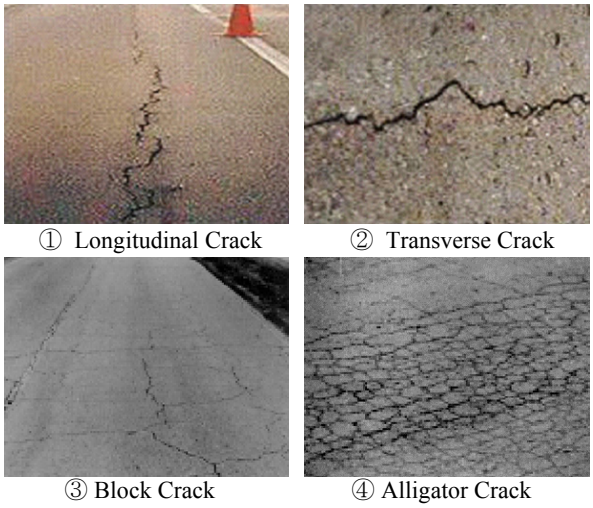
This study begins by describing the conventional crack sealing process in Korea as well as discussing some of the major research problems associated with the automation of pavement crack sealing. The system components of the developed APCS and machine vision algorithm are then illustrated. Performance(productivity) evaluation results of the APCS are discussed as well. Finally, conclusions are made concerning the value of automated pavement crack sealing and the applicability of the algorithms and tools presented in this study.

2. MAJOR RESEARCH PROBLEMS AND RELATED WORKS

2.1 Conventional Crack Sealing Process

In general, crack patterns existing on asphalt pavements are classified into the following four categories: 1)longitudinal, 2)transverse, 3)block, and 4)alligator cracks(Fig. 1). Among those, longitudinal,

transverse, and block cracks are mainly repaired by sealing, while overlay or patching is used for repairing alligator cracks.



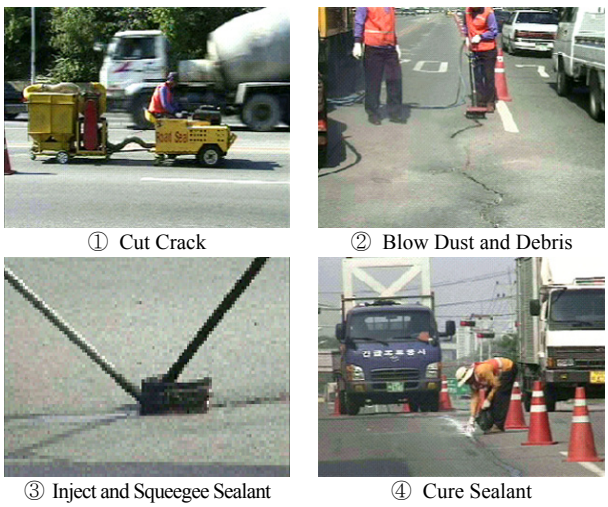
① Longitudinal Crack ② Transverse Crack

③ Block Crack ④ Alligator Crack

Fig. 1 Crack Patterns on Asphalt Pavements

Crack sealing is a preventive maintenance method, in which a sufficient amount of 170~180℃ sealant is placed along the spine of pavement cracks. In Korea, cutting cracks to be sealed in pavements is essentially required prior to sealing. As a result, sealed cracks can protect the sub-structure of the pavement from water and debris penetration; the crack sealing method thus can decrease crack broadening and prevent potholes. Such crack sealing procedures are as follows(Fig 2);

- Cut cracks to be sealed (width; 1.2~2cm, depth; 2~2.5cm) according to the construction specification regulation
- Blow dust and debris in cut crack network
- Seal by injecting 170~180℃ sealant into the cut cracks
- Finish the surface of sealed cracks by squeegeeing
- Cure the sealant



① Cut Crack ② Blow Dust and Debris

③ Inject and Squeegee Sealant ④ Cure Sealant

Fig. 2 Conventional Crack Sealing Process

2.2 Major Research Problems

For automatically sealing pavement cracks, the end-effector(turret) of the crack sealer must accurately and quickly trace the spine of each crack network and inject sealant into the crack network. It is due to the fact that productivity and quality of crack sealer are very important for its commercialization as well as the acceptance by the maintenance personnel. Major research problems related to the development of a crack sealer are as follows;

(1) Crack network mapping and modeling

Pavement images shown by digital CCD camera commonly include not only real crack networks, but also a wide variety of noises such as oil marks, skid marks, previously sealed cracks and inherent noises. Therefore, an algorithm that can extract only crack networks from the pavement images including the noises must be developed. Also, the algorithm must be able to accurately model the exact locations(x-y coordinates) of the extracted crack network so that the turret of the crack sealer can inject sealant into the spine of each crack network to be sealed. Crack network mapping and modeling is thus one of the most important research problems in developing any type of crack sealer.

(2) Path planning

There are many different types of pavement crack shapes, with occasionally complex morphologies. Possible paths can easily exceed 1,000,000 [7]. Objectives for crack sealing include minimizing distance and tool state switching. For automated crack sealing, the primary objective of path planning is to quickly find an optimal path, guaranteeing traverse of any kind of crack morphology in a given work space. In this study, an optimal path planning algorithm has been developed to generate the shortest traversal plan in a given crack network.

(3) Manipulator and End-effector Control

A crack sealer has to have 4 degrees of freedom to accurately move and seal along the spine of the crack networks. That is, X-axis and Y-axis movements are required to move in any directions on 2D surface. Z-axis movement (telescoping function) is also required to guarantee that cracks in a rutted pavement are sealed properly. In addition, the turret of crack sealer has to be rotated to effectively blow, seal, and squeegee along the spine of the crack network. Therefore, a motion control system is required to direct the crack sealer along the X-, Y-, and Z-axis and to rotate the turret of crack sealer.

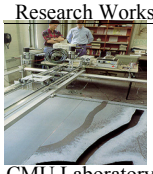
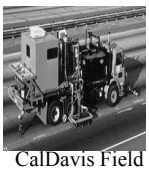
In the development of an automated construction and maintenance system including the APCS, the ultimate goal would be to develop a commercial system which can be operated at manual crew speed or faster with desired accuracy. That is, the system will have to meet the productivity and quality of

standard sealing crews in a conventional method. Compared to the conventional crack sealing operations, improving the operating speed in the APCS to be developed would be the most significant and critical factor for overall project success. Thus, effective and accurate crack detection, mapping and modeling, optimal path planning of the APCS and its manipulator and turret control will be the major tasks required to achieve the desired accuracy and operating speed.

2.3 Previous Research Works

During the last few years, several advanced countries have developed automated pavement crack sealing systems such as the CMU laboratory prototype(1990), CMU-UT field prototype(1992), CalDavis field prototype(1993), and UT field prototype(1995), ARMM(1999). Table 1 briefly describes the accomplishments and major concerns in each previous research work.

Table 1. Previous Research Works Related to the Automated Pavement Crack Sealing System

Previous Research Works	Accomplishments and Major Concerns
 CMU Laboratory Prototype(1990)	● Conceptual design of S/W and H/W for full automation ● Crack detection, mapping and representation using digital image processing ● Incomplete and unstable fabrication of H/W(X-Y manipulator) ● Excessive processing time in the crack detection, mapping and modeling
CMU-UT Field Prototype(1992)	● Development of a machine vision algorithm using sensor (vision and laser range scanner) fusion ● Development of path planning algorithm using linked data structure ● Fabrication of more robust H/W(XY-manipulator) and partial integration of S/W and H/W ● Partial verification of fully automated crack sealing process ● Excessive processing time due to still slow range scanning
 CalDavis Field Prototype(1993)	● Development of histogram based machine vision algorithm ● Lack of accuracy in crack detection, mapping and representation ● Limitations in types of crack to be sealed ● Employment of multiple manipulator arms ● Sealing speed of 16km/hour ● Failure to attract private contractors or government department due to the expensive selling price(over US $55,000 to 850,000
ARMM(1999)	● Suggestion of a man-machine balanced control process for effectively sealing pavement cracks ● Development of a machine vision algorithm (manual mapping, line snapping and manual editing) using graphical programming and user-friendly control software ● Development of greedy path planning algorithm using array data structure ● Need to improve the design of turret and machine vision algorithm[8]

The hardware of the automated pavement crack sealing systems was incomplete in the early stage. The software for mapping and modeling crack network to be sealed and path planning were not efficient in terms of productivity, quality and accuracy for commercialization. In addition, the hardware and software developed were not integrated properly, causing inaccurate and inefficient movement in the automated pavement crack sealing systems. The resulting deeper understanding of such early attempts and the recent advances in the relevant robotic technologies have thus motivated these researchers to develop and examine more advanced pavement crack sealer, which can accurately and effectively represent and seal pavement cracks under any work environments.

3. MAJOR SYSTEM COMPONENTS AND OPERATION PROCESS OF APCS

3.1 System Components of APCS

The APCS developed through this study is composed of the following three units: 1) tow truck, in which a system operator controls the APCS using a PC, 2) a sealant melter that supplies a 170~180℃ sealant to the APCS, and 3)crack sealing unit for blowing, sealing and squeegeeing cracks in pavements(Fig. 3).

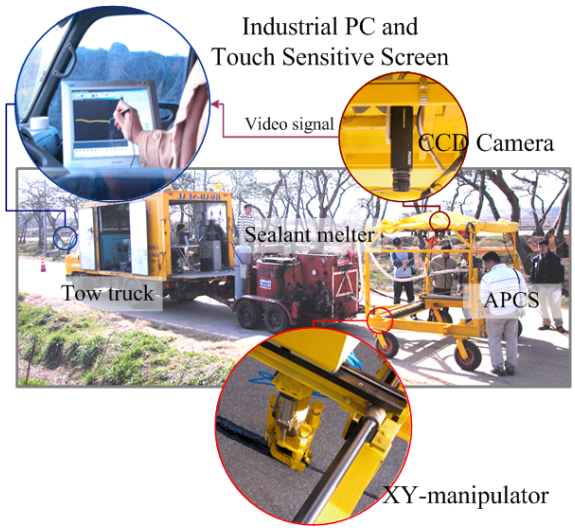


Fig. 3 Automated Pavement Crack Sealer(APCS)

The major components of the crack sealing unit of the APCS are as follows; 1) XY-manipulator with cart, gantry, turret, and CCD camera, 2) control box, 3) industrial PC with frame grabber and touch sensitive screen, and 4) power supplies. A machine vision software is also an essential component required to operate the APCS. This software is mainly composed of noise elimination, crack network mapping and modeling, and optimal path planning algorithms. In designing and fabricating the APCS, the following factors were especially considered.

- Designing the table(frame) of the XY-manipulator that is not twisted against the pavement level and various work situations
- Designing the machine vision algorithm that is not

affected by shade and pavement surface reflection
- Mounting the lighting system for working at night to minimize road-user-costs and increase productivity
- Rotating the turret of the APCS to effectively blow, seal, and squeegee the crack network to be sealed
- Designing turret structure for effectively sealing cracks in pavement with rutting(need to add telescoping function to the turret)
- Designing turret structure to effectively squeegee the sealant injected on the pavement cracks(turret with squeegeeing device of 'V' or 'U' shape)

Based on the results of the major considerations, a field prototype of the APCS was designed and fabricated as shown in Fig. 4. A more detailed description of the system components and their functions of the APCS is illustrated elsewhere[9].

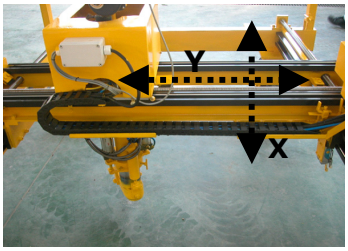
3.2 Crack Sealing Process of the APCS

The APCS uses an XY-manipulator with a rotating turret to blow, seal, and squeegee pavement cracks in one pass, thus greatly improving its productivity. While the manipulator is moving within its work space, its frame is stationary. Sealing cracks in one work area and then moving to the next work area is considered one work cycle. To control the APCS through a work cycle, the following six steps are required;

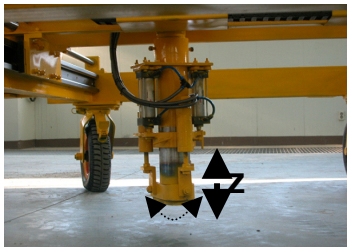
- Acquire pavement image including the crack network through digital CCD camera installed on the superstructure of the APCS and frame grabber board installed in the PC
- Stop the APCS if crack network exist on the operator's touch sensitive monitor
- Automatically eliminate noises for mapping and modeling the crack network(This process is required only for the case of fully automated crack network mapping and modeling to be explained in Section 4.1)
- Extract the exact spine of the crack network using the developed crack network mapping and modeling algorithm (In the APCS, the system operator can map and model the crack network to be sealed in a given work space by both automated and semi-automated methods selectively.)
- Automatically perform the optimal path planning, based on the results of mapping and modeling for the crack network
- The APCS performs air blowing work, injects sealant into the crack network and squeegees the sealant according to the results of the path planning

Fig. 5 describes the man-machine balanced, teleoperated pavement crack sealing process in an extremely simplified form.

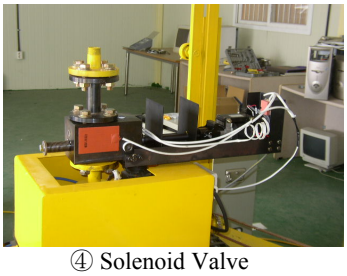
① XY-Manipulator



② Gantry and Cart



③ Turret with telescoping function


④ Solenoid Valve

⑤ Control Box

⑥ Industrial PC and Touch Screen

⑦ Air Compressor and Generator

⑧ CCD Camera

⑨ APCS in Field trial

Fig. 4 Field Prototype of the APCS

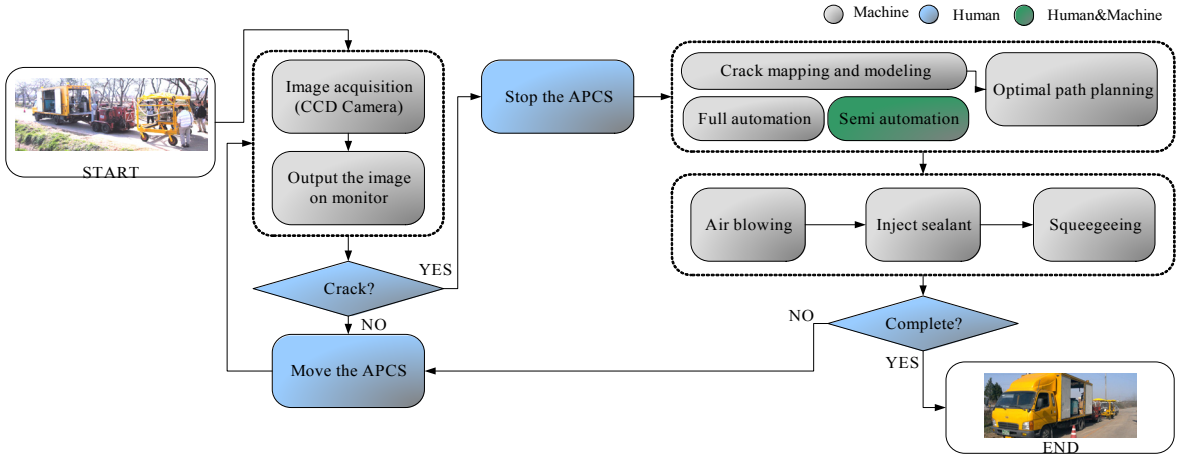


Fig. 5 Operation Process of the APCS

4. A MACHINE VISION ALGORITHM FOR AUTOMATED CRACK SEALING

In general, crack network mapping and modeling algorithm can be sensitively affected by conditions such as shade, intensity of pavement surface, and brightness. Therefore, in the APCS, the crack network detection, mapping, and modeling is operated in two ways: 'full automation' and 'semi-automation'. A unique machine vision algorithm has been developed for the automation of pavement crack sealing.

4.1 Fully Automated Crack Network Detection, Mapping, and Modeling

Fully automated crack network detection, mapping, and modeling process mainly includes 'binarizing and noise elimination' and 'crack network mapping and modeling'.

(1) Binarizing and Noise Elimination Algorithm

A binarizing and noise elimination algorithm must be developed so that the turret(end-effector) can accurately trace the exact spine of the crack network and inject sealant into them. Binarizing aims to effectively distinguish crack network from the noisy pavement image. The binarizing algorithm, which is designed to automatically set up a threshold value, represents the intensity of pavement image(Fig. 6-①) as black(0) and white(255)(Fig. 6-②). Crack network is randomly extracted after the binarizing process. Therefore, this study developed a noise elimination algorithm for the perfect extraction of crack network in a given work sapce. The noise elimination algorithm is performed as follows.

- Grouping connected pixels with the binarized result image
- Extracting the features of each group
- Automatically evaluating the group according to the average intensity, dimensions, circumference, circumference-dimension rate, diameter, thickness, and roundness ($4\times\pi\times A/L^2$) to eliminate noises completely (Fig. 6-③).

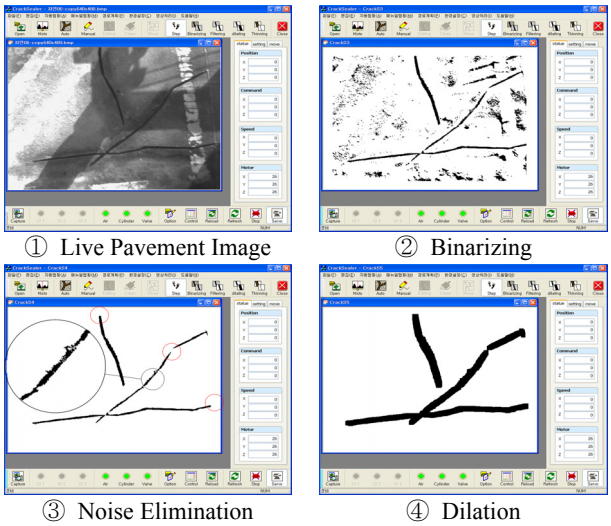


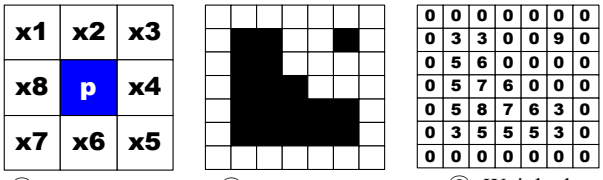
Fig. 6 Binarizing, Noise Elimination and Dilation Process

As shown in Fig. 6-③, the result of the noise elimination process algorithm shows a rough boundary of the crack network and unconnected pixels in the inner part of each crack line. Thus, this study applied the dilation process to the image in which noise was eliminated(Fig. 6-④).

(2) Crack Network Mapping and Modeling Algorithm

In this study, an edge thinning algorithm was used for automatically mapping and modeling crack network extracted after binarizing, noise elimination, and dilation process. The objective of the edge thinning algorithm is to erase the outline(edge) of each crack line in the network until one pixel remains. As a result, remained pixels are located in the spine(center) of the crack network, and connected to each other in the same group. However, most of the previous edge thinning algorithms such as those of Suen[1], Wang[2], Guo[3], Hall[4] and Zhang[5] developed to effectively recognize alphabet letters could not be applied to the crack network mapping

and modeling in terms of time and accuracy. This study thus utilized a parallel edge thinning algorithm using a weighted number[6]. The parallel edge thinning algorithm is based on the 3×3 mask composed by 9 pixels, and a pixel 'P' has 8 pixels(X1~X8) nearby(Fig. 7-①). A weighted number is the number of black pixels existing the pixel 'P' nearby(Fig. 7-②).



①8-Neighbored Pixels ② Input Image ③ Weighed Number

Fig. 7 3x3 Mask and Weighted Number

A black pixel 'P' must be erased in the case of the same condition of Fig. 8 after the weighted number is determined.

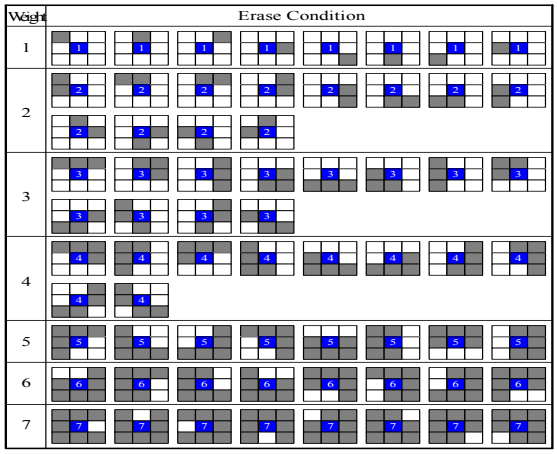
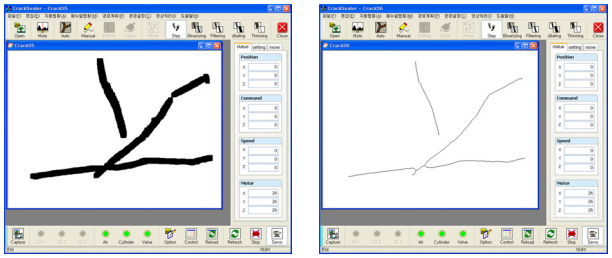


Fig. 8 Erase Condition of a Pixel According to Weighted Number

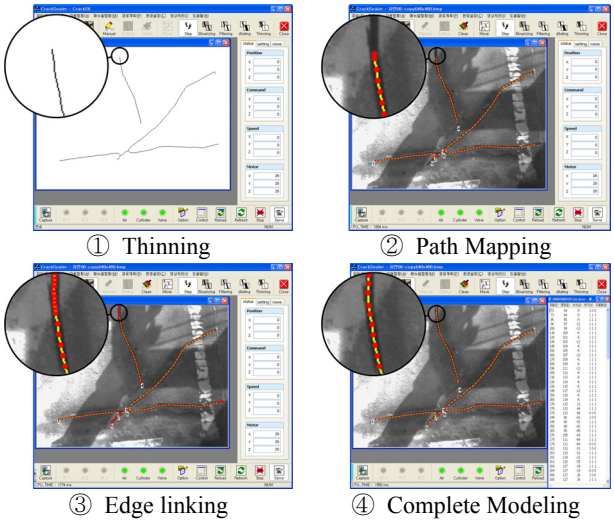
Fig. 9 is the result of applying the parallel edge thinning algorithm using a weighted number to a crack image. The thinned crack network(Fig. 9-②) is composed of several lines that are located in the spine of the crack network. The pixels of each thinned crack line are then saved in the memory so that the turret of the manipulator can move along the thinned crack line.



① Dilated Crack Image ② Parallel Thinning Algorithm

Fig. 9 Parallel Edge Thinning Algorithm Using Weighted Number

The result of the crack network mapping and modeling is represented for the operator to confirm errors(Fig. 10-②). Edge linking is then performed to connect pixels(Fig. 6-③) that might be erased wrongly in the process of binarizing or noise elimination(Fig. 10-③). Finally, the result of the automated crack network mapping and modeling is output as a text type and sent to a control program(Fig. 10-④).



① Thinning ② Path Mapping ③ Edge linking ④ Complete Modeling

Fig. 10 Automated Crack Mapping and Modeling

4.2 Semi Automated Crack Network Detection, Mapping and Modeling

Semi automated crack network mapping and modeling process is as follows(Fig. 11);

- Draw lines along the crack network
- Create node points on the drawn lines at regular intervals
- Create 5 x 41 pixel sized local boxes centered on the node points
- Perform local binarizing(0;background, 1;crack) in the created local boxes
- Move node points on the drawn lines into the center of gravity of the largest set composed '1'
- Show the result of crack network mapping and modeling on the touch screen in order to confirm errors
- Perform manual editing, if any errors exist in the result of crack network mapping and modeling

The test results showed that the semi automated crack network mapping and modeling algorithm was superior in terms of accuracy over the fully automated crack network mapping and modeling algorithm, but inferior in terms of productivity. Using neural network, the fully automated crack network mapping and modeling algorithm illustrated is currently being upgraded in order to guarantee superior performance in terms of both accuracy and productivity.

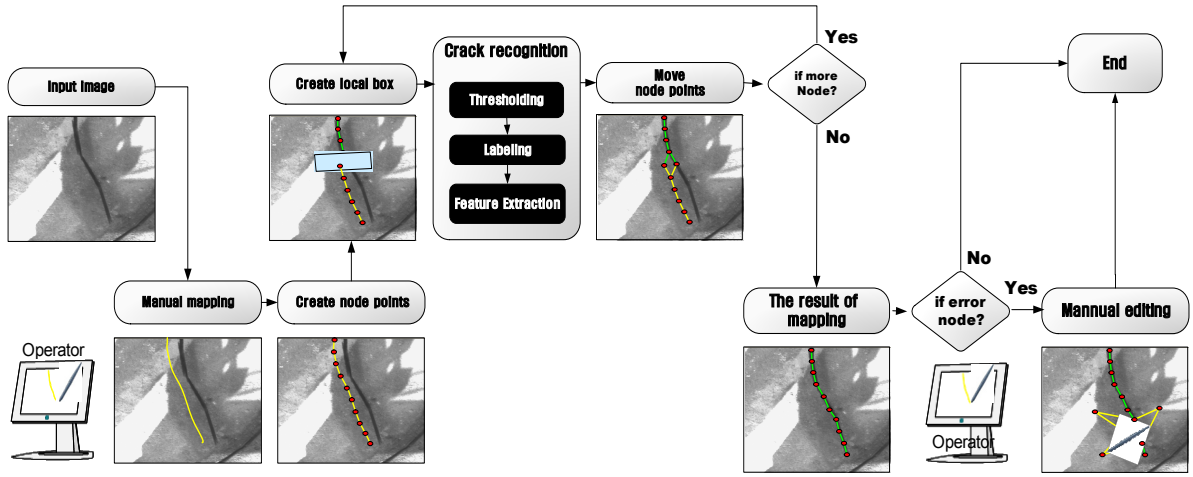
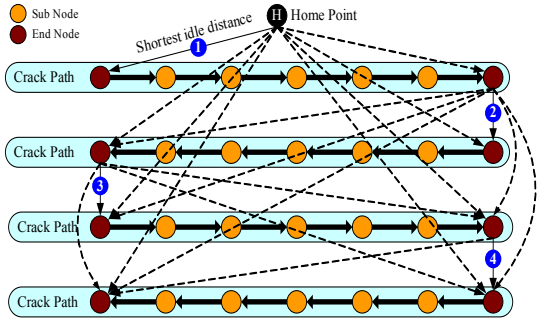


Fig. 11 Semi-Automated Crack Network Mapping and Modeling

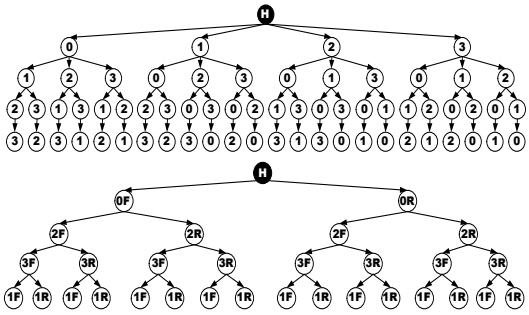
4.3 Optimal Path Planning

If there are several lines in the crack network extracted from a pavement image, the number of path is 2^n x n!. Greedy path planning algorithm was designed for crack sealing in the past[7]. The nearest node point from home point among the end node points of each crack network is the start node point for sealing, and the turret injects sealant along the crack network until the turret reaches the other end node point in the greedy path planning algorithm(Fig. 12-①, ②). However, the path planned by the greedy algorithm is not often the optimal path. This study thus developed an optimal path planning algorithm which can always provide the shortest path. In the optimal path planning algorithm, a computer calculates the lengths of all paths so that the shortest path can be selected(Fig. 12-③, ④). The results of test showed that the optimal path planning algorithm is effective if the number of crack lines in a network is 6 or less, and the greedy path planning algorithm is useful if the number of crack lines in a network is more than 7.

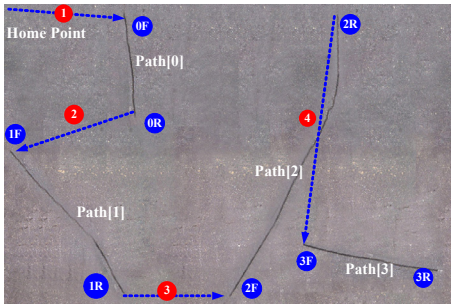
The control program developed is designed to automatically select a path planning algorithm according to the number of crack lines in a given network.



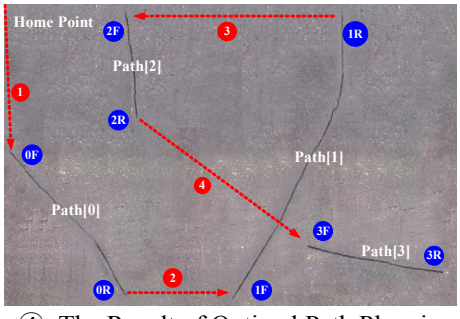
① Greedy Path Planning Algorithm



③ Optimal Path Planning Algorithm



② The Result of Greedy Path Planning
(Idle Path Distance= 945Pixels)



④ The Result of Optimal Path Planning
(Idle Path Distance= 882Pixels)

Fig. 12 Path Planning Algorithm

4.4 Integration of Hardware and Software

The APCS is mainly composed of an image capture module, machine vision module, and hardware control module. The integrated system of hardware and software is required to allow the APCS to accurately blow, seal, and squeegee along the spines(x, y coordinates) of each crack lines in a crack network extracted through the mapping, modeling, and path planning process. The image capture module and hardware control module are developed as a type of a dynamic link library(DLL), and imported into the machine vision module. The system operator can easily control the APCS with user-friendly graphical interface(Fig. 13).

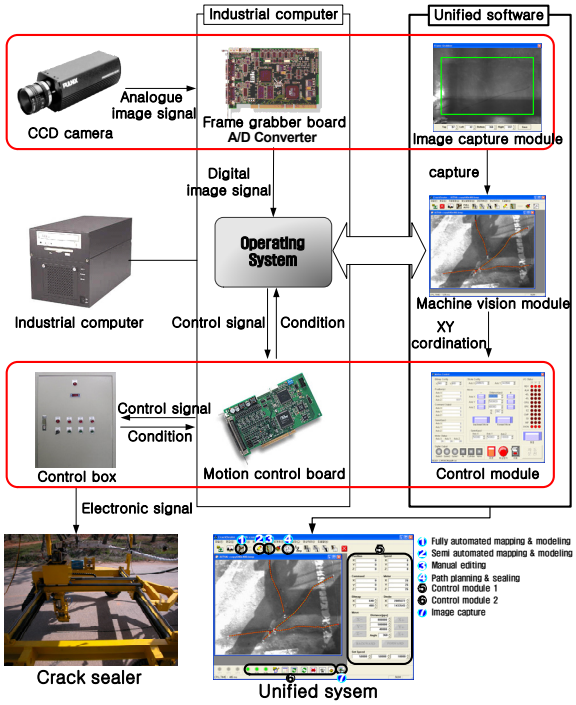


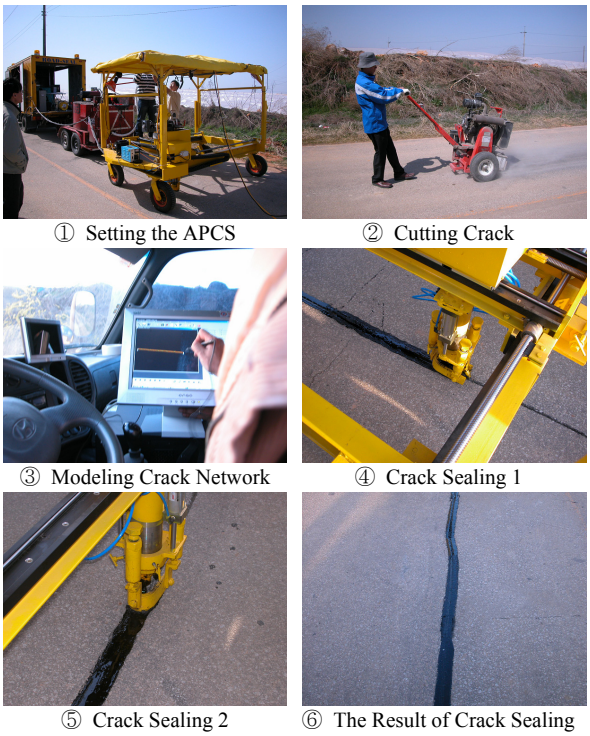
Fig. 13 Integrated System Architecture of APCS

5. FIELD TEST RESULTS

5.1 Field Demonstrations of the APCS

This study performed several laboratory tests and 3 field demonstrations to complete the prototype of the APCS. Especially, the field demonstrations were performed to evaluate the overall performance (productivity, quality and safety) of the developed APCS(Fig. 14). The field demonstration procedure is as follows;

- Connect the tow truck, sealant melter, and XY-manipulator
- Set up the computer and touch sensitive screen in the tow truck cabin, and connect them to the control box.
- Connect the control box to a XY-manipulator with a control cable
- Move the APCS to the work space
- Calibration of a work space
- Acquire image, and map and model crack network to be sealed
- Blow, seal, and squeegee the crack network



① Setting the APCS ② Cutting Crack

③ Modeling Crack Network ④ Crack Sealing 1

⑤ Crack Sealing 2 ⑥ The Result of Crack Sealing

Fig. 14 Field Demonstration Procedure of the APCS

The results of the field tests showed the followings: 1) the major components(cart, gantry, turret consisting of the XY-manipulator) of the APCS were moved adequately according to the on/off trigger signals from the machine vision and control software; 2) The turret was moved accurately along the spines of each crack network, and injected the sealant into them; 3) 'U' typed squeegee pressed sealant effectively; 4) The normal speed of the turret was measured to be about 18~20cm/sec; 5) The accuracy of the machine vision algorithm including noise elimination, crack network mapping and modeling, and path planning was measured to be over 86%; and 6) Quality of work done was on the whole excellent. On the other hand, the errors in the machine vision algorithm were correctly adjusted by manual editing with rubber banding capability so that the accuracy of the vision might be 100%.

5.2 Productivity of the APCS

This study measured the productivity of the developed APCS to compare with that of a conventional crack sealing method that generally shows the productivity of 1.2km/day with about 2 trucks, 1 sealant melter, and 12 labors. The test conditions for automation and conventional method

were set up as similar as possible. Table 2 shows the number of resources required to seal pavement cracks with the automation method, and Fig. 15 shows the real test bed that was made to measure the productivity of the APCS.

Crack networks in the test bed were composed of two transverse cracks of a total length of 4 m and three longitudinal cracks of 34.9m. The result of image processing time measurement shows that the time required for image capture, digital image processing, and path planning are 0.1sec, 0.5sec, 0.3sec, respectively.

Table 2. Resources for Automated Crack Sealing

Labor		Equipment	
Operator	1	tow truck	1
Labor for cutting	1	sealant melter	1
Cleaning and Blowing	1	XY-manipulator	1
Labor for controlling sealant melter	1	-	
Talc	1	-	
Foreman	1	-	
Total	6		3

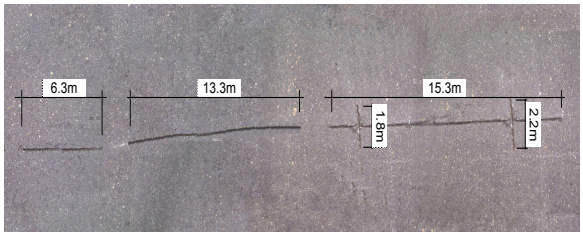


Fig. 15 A Test Bed to Mesure Productivity

The real work space of the APCS is 1.55m × 0.9m, and the speed of the turret is about 20cm/sec as 'not sealing', 18cm/sec as 'sealing'. This study measured the productivity of the developed APCS based on the productivity data and evaluation model(Fig. 16).

In the productivity evaluation model, the sum of length of crack networks(L) divided by the moving time(T) and the image processing time(I) and the crack sealing time(S) gives the productivity(P) of the APCS. The prototype of the APCS should stop 44 times for sealing the entire crack networks in the test bed illustrated in Fig. 15. Work time required in each work space was measured with stop-watch method. As a result, the productivity of the APCS is 3.3m/min based on the measured productivity data and evaluation model(Fig. 16).

- The productivity of the APCS(P)

$$P = L / (T+I+S) = L / [(Tb+(Ta \text{ or } Tc)) + (Ia+Ib+Ic) + S]$$
$$= 38.9m / [(173+262) + 40 + 216)] = 38.9m / 691sec$$
$$= 0.057m/sec \rightarrow 3.3m/min$$

Therefore, the daily productivity of the APCS would be 1.59km/day(=3.3m/min × 480min/day). When compared with the productivity of a conventional crack sealing method(1.21km/day), that of the APCS was higher by as much as 0.39km/day. The productivity of the APCS would be much higher, when considering the night time operations and possible improvements (size of the XY-manipulator) of the developed APCS.

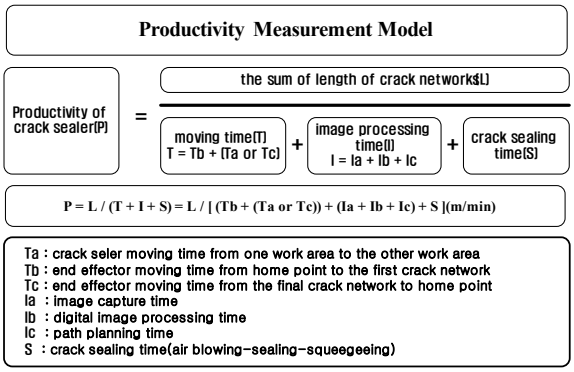


Fig. 16 Productivity Measurement Model

6. CONCLUSIONS

In conclusion, the advantage of the automating conventional pavement crack sealing process is clear. Recent field trials of the full-scale APCS appear to support this conclusion as well.

In this study, a machine vision algorithm for noise elimination, crack network mapping and modeling, and path planning was developed. The test results of the developed machine vision algorithm showed that its accuracy was over 86%, and the processing time was about 0.9sec/image. The prototype of the APCS was developed by analyzing and investigating previously developed pavement crack sealing systems and enabling state-of-the-art technologies. Laboratory and field demonstrations of the developed APCS were conducted for evaluating and verifying its overall performance and technical feasibility. Major components of the APCS were operated without any problems and the blowing, sealing and squeegeeing speed of the turret was measured to be about 18~20cm/sec.

Six labors were required to seal cracks with the APCS, while the conventional crack sealing method required 11~12 labors. Daily productivity rate of the APCS was analyzed and found to be 1.59km/day. The reduction in crew size and the increase in productivity of the automated sealing process will be also translated directly into significant potential cost savings.

Finally, it is anticipated that the man-machine balanced, teleoperated crack sealing process presented in this study would be applicable to a wide variety of infrastructure cracks and joint sealing. Partial modifications of the algorithms and tools presented in this study would eventually have broader applications in automation of infrastructure inventory geometric data acquisition and use or inspection and maintenance of civil works.

ACKNOWLEDGEMENTS

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Experimental Studies of Two Force Control Algorithms for a Crack Sealing Robot in Highway Maintenance Technology

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***Abstract*:** This paper presents experimental studies of force control algorithms for a crack sealing robot. The crack sealing robot is built as a test-bed to regulate contact force on the ground for a better task. Force tracking performances of two main force control algorithms, explicit force control and impedance force control, are compared experimentally. Experiments are conducted to test the robustness of control algorithms under unknown surface condition of the road. Experimental results show that performances of two force control algorithms are very comparable.

Keywords : crack sealing robot, impedance force control, explicit force control

1. INTRODUCTON

Works at the road are very dangerous jobs for workers due to fast passing cars. To protect workers from dangerous situation on the road, automation of the whole working process by reducing the number of workers at present working environment will be one solution. There have been extensive researches of autonomous maintenance and construction for highway in the USA. The advanced highway maintenance and construction technology (AHMCT) center at UC Davis is one of the leading groups in this field. Their main goal is to automate all the maintenance works related with highway.

Recently, as a project, they have built a crack sealing automobile that seals cracks on the highway by following almost straight line of cracks [1]. The purpose of the crack sealing automobile is to seal cracks on the pavement autonomously. Cracks may cause uncomfortable driving condition to the driver, even the deadly traffic accident.

In the similar way, an autonomous crack sealing robot is built for feasible application. Before sealing crack, the crack must be detected by a laser sensor and a camera sensor, then cleaned for a better sealing job. To perform a brushing task before sealing, force control to the ground is applied to maintain constant contact.

The hybrid force control and the impedance force control are two main streams [2,3]. Based on these two control strategies, various modified force control algorithms have been proposed [4-6]. The explicit force control algorithm is formulated from a simple PID control of force errors [6]. The force tracking impedance control algorithm has been proposed to specify a desired force directly and to perform force tracking under unknown environment [7-8]. The fuzzy and neural force control methods to deal with unknown environment have been proposed [9, 10].

In this paper, as an extension of our previous researches, experimental studies are conducted to confirm the theoretical analysis [8,11-12]. Performances of the force tracking impedance control and the explicit PID control algorithm are tested. The sealing robot is required to maintain a desired force by following the trajectory on the curved wood and the curved steel environment. To test the robust performance on the unknown environment of the proposed force control algorithms, the environment is designed as the curved shape which is arbitrarily unknown to the robot. And at the same time, two different materials of the environment are used to test the robustness of the control algorithm for unknown stiffness.

Extensive experimental studies of two main force control algorithms, the impedance force control and explicit force control, are conducted. Experimental results show that two controllers are very robust under unknown environment uncertainties. Performances of two force control algorithms are quite good and stable under unknown environment. It turns out that the explicit PID force control method is better in implementation point of view while less contact force is observed under the impedance control method. In force tracking, two control methods are comparable.

2. OVERALL SYSTEM STRUCTURE

The developed overall crack sealing robot structure

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is shown in figure 1. The robot is a kind of wheeled drive robots equipped with a gantry typed xyz robot in the middle. The robot consists of three parts: a crack detecting part, a crack sealing part, and an actuator part. The crack detecting part hidden in a black box has a laser sensor and a camera sensor to detect cracks. Abrupt step change of the crack in sensed information by the laser sensor is obtained by the camera.

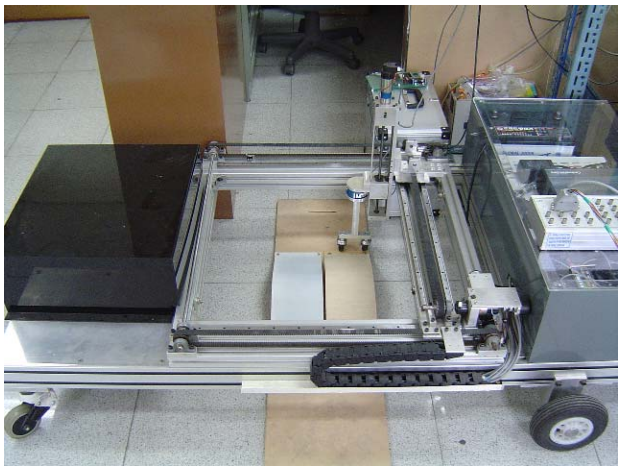

Fig. 1. Overall system structure

The position of the detected crack can be mapped to the robot coordinate to drive wheels. The robot is required to make the crack position be aligned in the middle of the robot wheels. In this way, the robot tracks the crack. The crack sealing part has a gantry typed robot that moves xyz directions. The force sensor is attached to the end of the z axis so that the normal force to the ground is regulated. The brushing device will also be equipped at the end of z axis in the near future. Two rollers are distantly located apart each other because the crack will be located between two rollers. The actuation part has batteries, computers, actuating motors, and other necessary devices.

3. IMPEDANCE FORCE CONTROL ALGORITHM

The impedance control method regulates force by selecting impedance parameters correctly. Even though it has lack of force tracking capability, the dynamic relationship between the robot and the environment is considered. Here, the force tracking impedance control is summarized [7,8,10-12].

The original impedance closed loop function is given as

$$m\ddot{e} + b\dot{e} + ke = f_e \,, \qquad (1)$$

where $e = x_r - x$ and x_r is the reference location, x is the actual location, f_e is the external force, and m, b, k are impedance gains. By setting appropriate gains, a desired force can be achieved.

To give the force tracking capability to the robot, equation (1) can be reformulated as

$$f_e - f_d = m\ddot{\varepsilon} + b\dot{\varepsilon} \,. \qquad (2)$$

where $\varepsilon = x_e - x$, x_e is the environment location and f_d is the desired force.

Since the external force can be modeled as the spring system $f_e = -k_e\varepsilon$, substituting it into equation (2) becomes

$$-f_d = m\ddot{\varepsilon} + b\dot{\varepsilon} + k_e\varepsilon \,, \qquad (3)$$

If the environment x_e is not accurately available, in general it is true for most of cases, $f_e = f_d$ cannot be guaranteed.

Let x_e' include uncertainty in x_e so that $\delta x_e = x_e' - x_e$. Define $\varepsilon' = \varepsilon + \delta x_e$, replacing ε with ε' at (3) yields

$$m\ddot{\varepsilon}' + b\dot{\varepsilon}' = f_e - f_d \,. \qquad (4)$$

δx_e can be minimized to a certain accuracy by the user.

However, if f_d and x_e are time varying, there will be a force tracking error. The force has the error in tracking a desired force. To make $f_e = f_d$ at (4), the simple adaptive method has been proposed as below. Equation (4) can be reformulated as

$$m\ddot{\varepsilon}' + b(\dot{\varepsilon}' + w) = f_e - f_d \,, \qquad (5)$$

where

$$w(t) = w(t-\lambda) + \eta\frac{f_d(t-\lambda) - f_e(t-\lambda)}{b} \,, \eta > 0 \,, \qquad (6)$$

η is an adaptive gain and λ is the sampling time.

The stable condition of an adaptive gain can be found as

$$0 < \eta < \frac{b\lambda}{b\lambda + m} \,. \qquad (7)$$

More detailed stability analysis of this algorithm can be found in the paper [7].

The adaptive impedance force control block diagram is shown in figure 2. Since the z axis of the gantry robot is force controlled and the z axis is actuated by a ball screw driven by a DC motor, the robot dynamics can be considered as a simple linear

system. So the control law becomes very simple as below

$$\tau = \frac{1}{m}[b(\dot{\varepsilon}' + w) + f_d - f_e]. \qquad (8)$$

Figure 2 shows the control block diagram of the impedance force control algorithm.

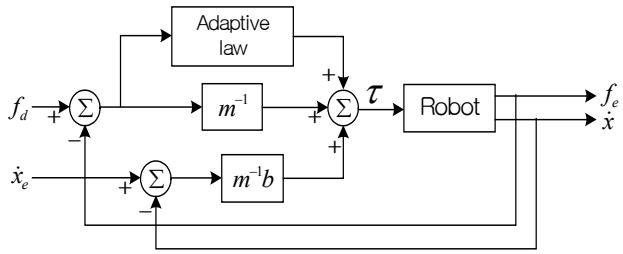

Fig. 2. Proposed impedance control

4. EXPLICIT PID FORCE CONTROL ALGORITHM

The explicit PID force control algorithm is a kind of the hybrid force control method that has a position-controlled direction and a force controlled direction selected by a selection matrix. Here, for simplicity, the crack sealing robot has only z direction to be force controlled. So, the controller for the force-controlled direction is formed as a PID controller type that is formed with force errors.

The control law is given as

$$\tau = k_P e + k_D \dot{e} + k_I \int e dt \qquad (9)$$

where f_d is a desired force and k_P, k_D, and k_I are controller gains.

The control block diagram is depicted in figure 3.

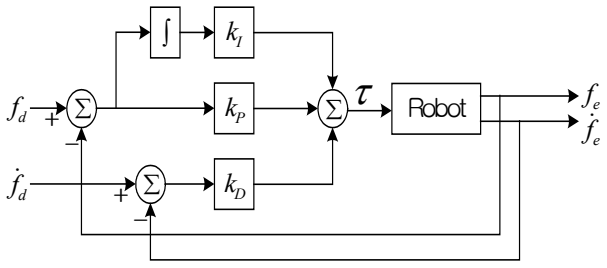

Fig. 3. The explicit PID control block diagram

5. EXPERIMENTS

5.1. Experimental setups

The force control experimental setup is shown in figure 4. Environment is made of wood and steel to have unknown stiffness, and has the round shape to give unknown environment location to the robot. Since z axis is actuated by a ball screw driven by a dc motor, the gravity force of the robot is compensated. Considering one axis control, Coriolis and centrifugal forces can also be neglected. Since the robot is very much linearized for a force tracking task, the dynamic compensation for the robot is not considered.

The robot does not have any knowledge about the environment. The robot is required to track the environment with a regulated force. The JR3 force sensor is used to detect force and rollers are attached to the end-effector to minimize friction force. The normal force to the ground is regulated. The sampling time is 10ms.

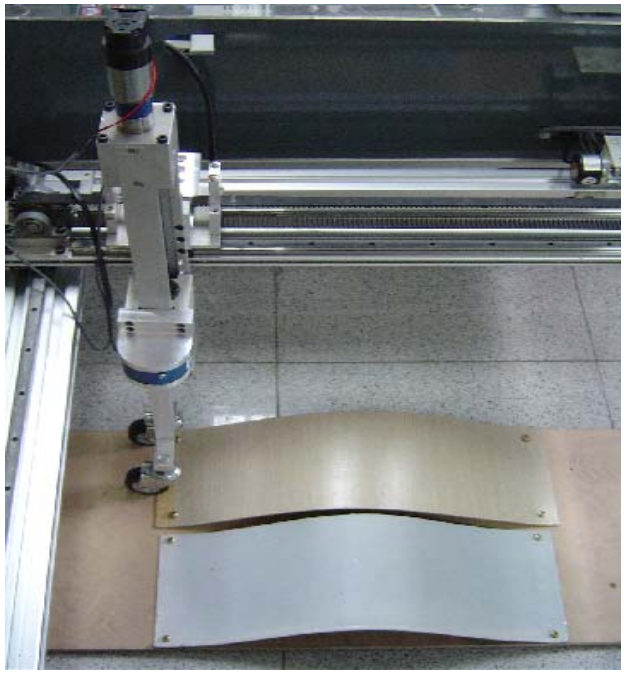

Fig. 4. Experimental setup

5.2. Force tracking for wood environment

First, force control algorithms are tested for the wood environment. The desired force is 20N. Initially, the robot already made contact with the environment. So the transition effect from free space to contact space is minimized.

1) PD control

The explicit PD force control is tested to regulate contact force. The controller gains are *kp* = 20 and *kd* = 0.2. Fig.5 shows the tracking results for force and position. The controller maintains the stability, but we clearly see that force tracking errors are observed. The shape of wood environment is clearly shown. We see that more force is detected in climbing up direction and less force is detected in climbing down direction. Next, to minimize the force tracking error,

the PID controller is used.

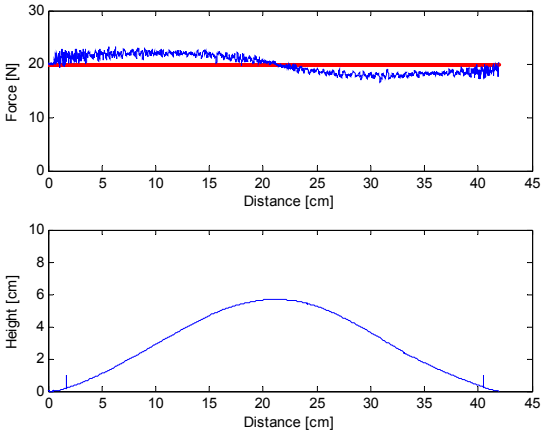

Fig. 5. Tracking results of PD control

2) PID control

To eliminate those tracking errors, PID controller is used. The controller gains are selected as *kp* = 20, *kd* = 0.2, and *ki* = 0.2. The tracking results are shown in figure 6. We clearly see that tracking errors are minimized.

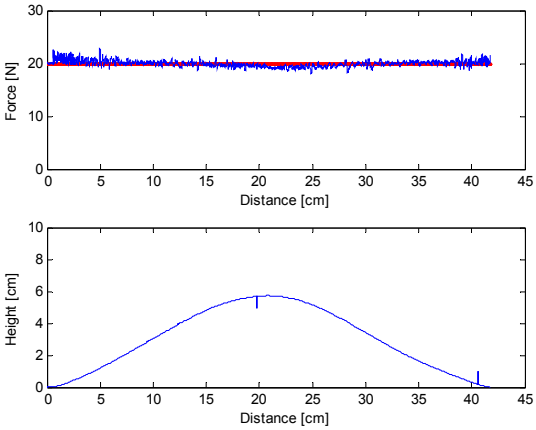

Fig. 6. Tracking results for PID controller

3) Impedance control

The impedance controller gains are set as m=0.1,b=1, η=0.05.

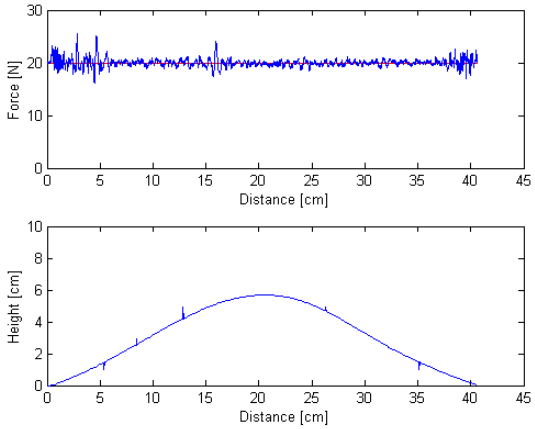

Fig. 7. Impedance force tracking control for wood

This adaptive gain value is selected to satisfy the stability condition given in (7) as $0 < \eta = 0.05 < \frac{0.01}{0.01+0.1} = 0.09$.

Figure 7 shows the 20N force tracking as well as the position tracking by impedance force control. The traveling time of the robot is about 40 seconds. Force is well regulated at 20N without losing its stability.

5.3 Force tracking for steel environment

Next experiment is done for the steel environment. Usually for the rigid environment, more compliance is given to force control to make the system stable. Initially, the robot made contact with the steel environment as before. And then the robot is required to move on the steel. As before, a force value is regulated as 20N. Since the stiffness of the steel is much larger than that of the wood, force control becomes more difficult.

1) PD control

The controller gains are *kp* = 20, *kd* = 0.2, and *ki* = 0. As expected, in figure 8, more oscillatory behavior in force tracking can be observed. Force tracking errors are still present. Deviated tracking error is similar to that of figure 5, but it is more oscillatory. These errors can be minimized by I controller of the PID controller.

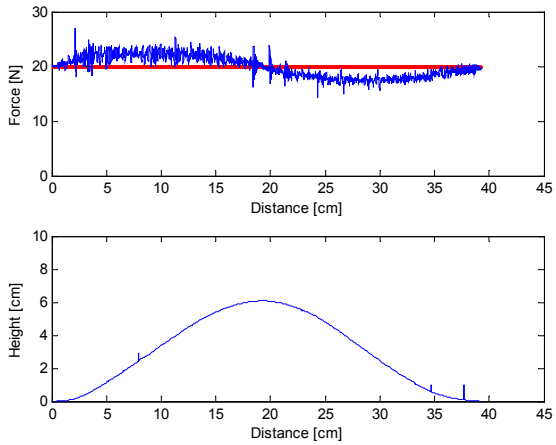

Fig. 8. Tracking results for PD control

2) PID control

The PID controller gains are *kp* = 20, *kd* = 0.2, and *ki* = 0.2. In figure 9, the force tracking error is eliminated. The corresponding position plot is also shown. Glitches appeared in position tracking plots are due to plotting problem in PC. Those should not be considered as actual data.

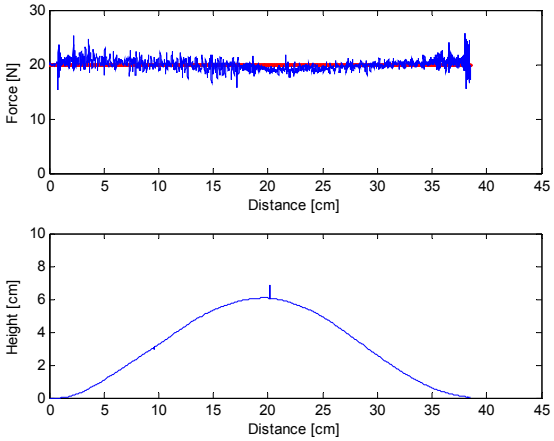

Fig. 9. Tracking results for PID control

3) Impedance control

Comparing the force tracking result plots of figure 7 and figure 10 shows that larger oscillation in force tracking can be observed in the case of steel environment. The corresponding position tracking data are also plotted. We clearly see from position tracking data that the robot follows the steel environment well. The controller gains for the experiment are m=0.1,b=1, η=0.05.

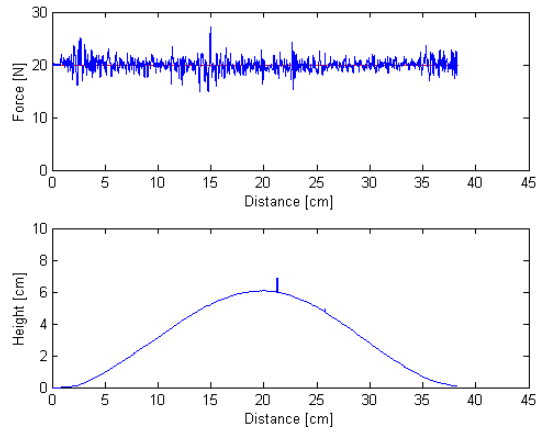

Fig. 10. Impedance force tracking control for steel

5.4. Force tracking for both wood and steel

The last experiment is to track on both wood and steel by making transition from free space to contact space. The robustness of the controllers is tested under unknown stiffness without changing controllers' gains

The initial position of the robot is located about 2 cm above the ground. The robot starts moving toward to the ground and makes contact at about 2secs. So the large force overshoot can be observed at contact in figures 11 and 12. And then the robot follows the wood environment and the steel environment while regulating a desired force. The whole traveling time is about 2 minutes.

1) PID control

Even if the large force overshoot occurs at initial contact, the contact force is well maintained without losing its stability. Position tracking plot shows the actual tracking shapes of the wood and steel environment of the robot. Force overshoot in the middle occurs due to the irregular surface condition.

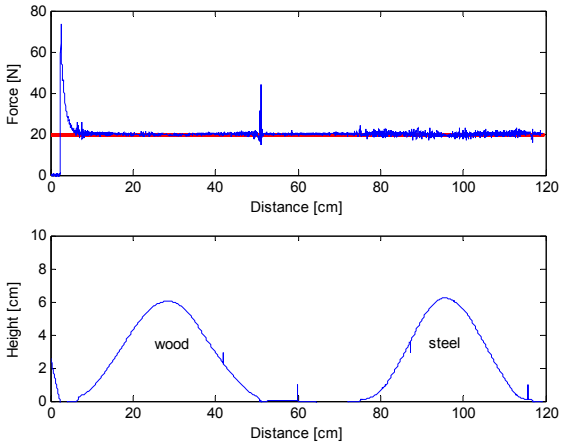

Fig. 11. PID force tracking control for steel

2) Impedance control

Figure 12 shows the force tracking result by the impedance control method. We clearly see from figure 12 that force tracking is quite good. As expected, force tracking for wood environment is better than that for steel environment. Contact force is somewhat smaller than that of figure 11.

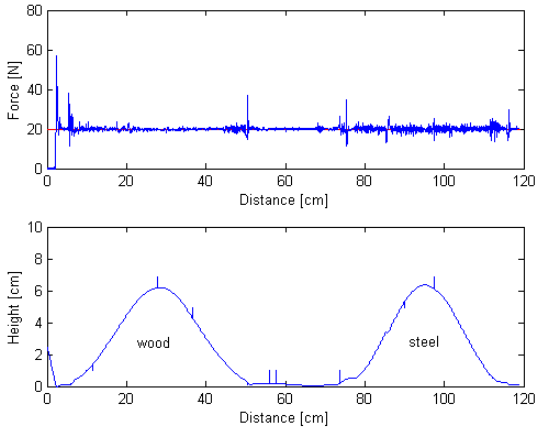

Fig. 12. Impedance force control for wood and steel

6. CONCLUSIONS

This paper presented experimental studies of the force control algorithms for the crack sealing robot. The crack sealing robot is developed to find crack and tracks crack on the pavement while the contact force on the ground is regulated. Impedance force control algorithm and explicit force control algorithm are tested under unknown environment. Two force

control methods performed stable force tracking under unknown environment stiffness and location. The explicit force control has an advantage in implementation because only force information is required, while impedance control requires both position and force information. However, impedance force control shows less contact overshoot.

In the future, experiments will be conducted on real pavement outside.

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DEVELOPMENT OF AUTOMATIC ROAD MARKING REMOVING EQUIPMENT USING HIGH PRESSURE WATER-JET

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Abstract : Present removal work for road markings has been time-consuming and labor intensive because it has been performed manually using shaving type equipment. The traditional process causes traffic delay due to the passing control, resulting in unexpected accidents to workers working at dangerous road circumstance. Besides, the current shaving method leads to air pollution as well as explosive accidents caused by propane gas. Thus, we have studied to develop the automatic removing equipment which consists of a high pressure water-jet system, automatic control system and mobile system: the water-jet system consists of an intensifier and nozzles to give a high pressure and spray on the marking; the automatic control system is composed of one axis robot using a hydraulic servo actuator controlled by a lever; and the mobile system employs a truck which plays an important role for transport of equipment and forward movement in a removal process. In this paper, we have analyzed the characteristics of road markings and investigated current removing methods in this field. In addition, we have organized and designed automatic removing equipment. We have also made a basic experiment to find out the optimized spray condition such as spray distance, spray angle and injection pressure.

Keywords : work process analysis, water-jet system, road marking, intensifier, lever system,

1. Introduction

1.1 Background and objective of the study

To fulfill the original function as a road, a road must be managed and maintained in a safe, comfortable and convenient manner. In this regard, the removing work of road markings shall be performed efficiently as one of the methods to maintain the road. However, current removing processes require many workers and much time, employing a traditional manual machine such as a shaving type machine. From a social and economic point of view, these kinds of manual tasks bring about social inconvenience and economic loss including traffic jam and unanticipated costs. Moreover, from a safety perspective, manual tasks trigger various dangers such as unexpected traffic accidents or exploration of propane gas used for ground finishing, leading to health problem and environment pollution dusts and noxious gases. Accordingly, we feel keenly the necessity for the development of new alternative equipment.

The water-jet system, which already has been developed in 1960, means a machine spraying water compressed ultra-high pressure. This water-jet system is widely utilized for cutting and surface cleaning for basic materials. The innovative application of water-jet technology is expanded to such fields as electronics, mobile, machinery, construction and shipment with automated processes, easy-to-operation and manufacturing precision. The most significant advantage of this water-jet system includes low dust scattering, good working conditions and convenient automation for various applications.

Therefore, as a preliminary study for development of an automatic road marking removing equipment, this paper is designed to find out optimized spray condition including spray distance, spray angle and injection pressure by analyzing components and considerations of the equipment.

1.2 Methods of the study

In this paper, the following methods are used:

First, analyze current technical development both home and abroad.

Second, investigate the characteristics of various road

markings, especially marking standards such as length, width and paints from Standard Specifications of Korea Highway Corporation.
Third, analyze current removing processes through on-site investigation.
Fourth, find out considerations and major components of developing the equipment based on the above results.
Lastly, define appropriate conditions of performance for reliable equipment design.

1.3 Tendency of related technologies

Since domestic reference sites of developing water jet system-based removing road marking are hardly found, current trends of related technologies focus on foreign equipment developed by SUGINO Co., Ltd (Japan) and Jetedge Co., Ltd. (America).

The system developed by SUGINO Co., Ltd (Japan)[1] consists of independent five big units such as ultra high pressure pump unit, vacuum unit, water tank unit, hydraulic unit and removal machine. The characteristic of this equipment is to circulate water by filtering clearly using vacuum and disposal units. Despite these advantages, however, there are some difficulties of setting up the whole system and moving them in other places. Above all, it is noted to employ the environment-friendly water disposal method.

The highway stripe removal system developed by Jetedge Co., Ltd. (USA)[2] is the one most similar to our new equipment in the concept of loading whole units on a truck. However, it is difficult to apply this big removal system to our narrow road conditions, along with environment unfriendly structure.

2. Analysis of Major Components for Developing Equipment

2.1 Present conditions of road markings

We have investigated the Korea Road Traffic Act[3] and Standard Specifications of Korea Highway Corporation[4] to find out the standard and various road markings on the domestic highway.
The analysis shows that road markings have a variety of types, colors and sizes. Because our main target of removing is a general traffic lane, the width of lane is an important factor. The width of lane is generally about 15cm or a maximum of 20cm for central lines. As a result, 20cm is set to be a removable width, with extra width applied to the design.
Through a real field investigation, we analyzed other considerable conditions such as narrow working space, various road facilities and uneven ground conditions.

According to Korean Standards, three types of paints: hot spray type, hot melt type and water resoluble type are used as traffic paints. In this study, only hot melt type of paint is considered as a removing target for more effective analysis.

2.2 On-site analysis

For development of the new equipment, first of all, it is important to observe current work methods or processes in detail. By comparing current works with new processes, we can analyze productivity, quality, and improvement of road marking removing works if the development equipment is applied at a same field.
As shown in Figure.1, we have visited the work place to analyze problems occurred from the traditional road marking removing equipment. Also, we could set up the current working process of road marking removing.

Figure 1. Working field for road marking removing

The whole working process of current road marking removing is classified into three steps: the equipment check as preparation for the work; the repetition of removing work; and working field arrangement. As the second step, the actual removing process is broken down into six steps: setting of a safety panel; marking removing using shaving type equipment; road cleaning; heating by propane gas; ground finishing for removing traces; and movement for other place. Besides, these six processes are performed repeatedly, if necessary (Figure 2).

Figure 2. Diagram of the whole working process

The results of the field investigation and interviews with workers show that:
First, shaving type equipment has broken down an average of 2~3 times a day. In particular, hot summer weather causes asphalt melting and lumping, leading

to mechanical problem in shaving lumped asphalt such as overload. Second, a variety of dangerous factors caused traffic accidents and gas explosions. Third, when the equipment shaves road markings and asphalts together, a lot of dusts and noises with high decibel occur.

2.3 Analysis of main components

The analysis of various characteristics on road markings and removing methods enables us to obtain more efficient equipment to overcome the disadvantages of the current system. The new equipment removes markings not by manual shaving methods but by automatic spraying methods using ultra-high pressure water without damaging road surfaces.

The innovative equipment consists of a water-jet system including a nozzle for forming ultra-high pressure water and for spraying water on the road; an single axis manipulator system for moving the nozzle in x axis direction; a remote control lever system for controlling and operating equipment as a user's interface; a water tank for transporting and storing water; and a mobile system for loading this devices and moving the nozzle in y axis direction (Figure 3).

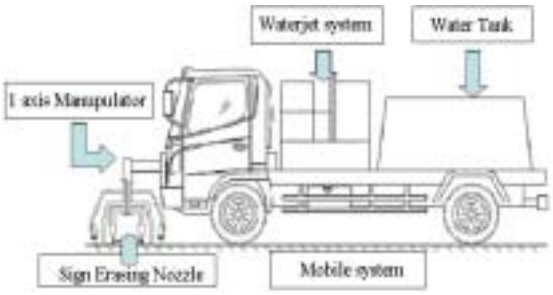

Figure 3. Concept map of the new equipment

3. Basic Design for Components

To design each component such as water-jet system, one axis manipulator system and control lever system, we have studied on various conditions, specifications and design standard for reliable operation

3.1 Water-jet system

In the design of high pressure water pump, first of all, the most important factor is maximum injection pressure. To obtain a satisfactory result in removing markings against unexpected road condition like unsmooth surface, type of paints, and double-paint, etc., we have designed water pump to inject water in the pressure of maximum 3,000 bar. To find the optimum conditions to remove markings, we would directly regulate the pressure of the water jet system in the field.

Water-jet system means that the device to use the concentrated power by injecting the water compressed with ultra-high pressure (1000 bar or higher) through the nozzle to convert potential energy into kinetic energy at sonic speed. Figure 4 shows the circuit diagram of water-jet system for removing road markings.

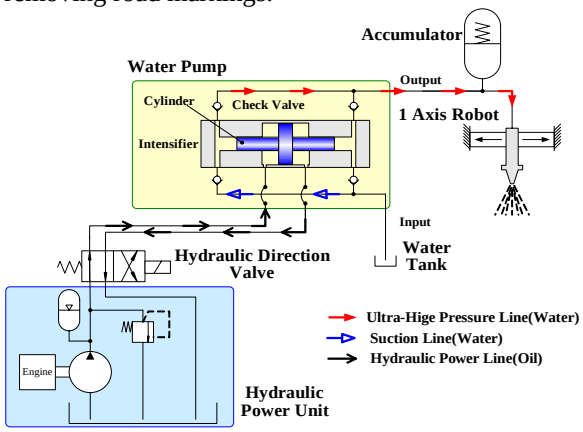

Figure 4. Water-jet system

Water-jet system (figure 5) is configured with hydraulic power unit, hydraulic valve, water pump, accumulator and nozzle. Hydraulic power unit driven by the engine functions from the driving source of water pump, that is, makes the piston in the cylinder reciprocate. Water pump is consisted of check valves to control the direction of the flow in inlet or outlet, and an intensifier to compress the water in ultra high pressure by the area ratio between piston and rod, what is called, Pascal's principle [5]. According to piston reciprocation by the action of hydraulic power unit, the water sucked from the water tank has been compressed in higher pressure. A nozzle connected with one axis manipulator sprays ultra high pressure water on the road markings. Also, the nozzle can be changed with 1-hole, 2-hole or other type. Accumulator will reduce the pulsation of pressure in outlet line.

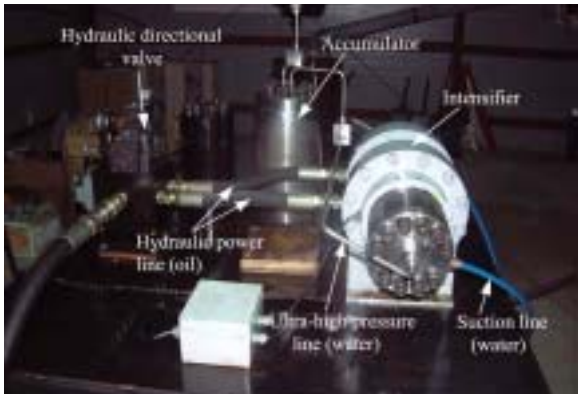

Figure 5 Configuration of water-jet system

3.2 One Axis manipulator

One axis manipulator system means

hydraulic servo actuator or cylinder [6] with a positional control sensor, Linear Variable Differential Transformer (LVDT), and can transmit input and output data by an industrial computer. This system is driven by the supply flow volume which is in proportion to the electric signal put from a hydraulic servo valve, and can be controlled with precision or accuracy. The target specifications of this system is the operating speed of maximum 400mm/sec, the repeat accuracy of less than 0.1mm and precision control with the load of 20kgf.
Figure 6 shows the control flow of one axis manipulator system.

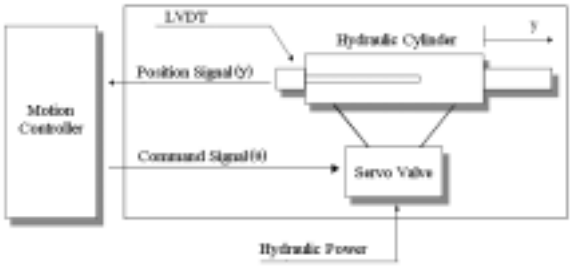

Figure 6. Concept of one axis manipulator

3.3 Control lever system

A control lever system is required to allow an operator to move the injection nozzle to the position he wants by simple lever operation in association with one axis manipulator. This lever system will be available by controlling one axis manipulator or hydraulic servo valve, an element which determines the direction of hydraulic servo actuator. The range of lever manipulation should be proportional to the magnitude of electric signal fed to the servo valve.

An axis lever is consisted of potentiometer, select switch, release switch, and trigger switch. Since the analog output signal generated by operating a lever and current drive unit communicate with PLC control program and electric unit in the controller, and is transferred to the servo valve, an actuator controller, to control the servo actuator or injection nozzle to desired position. Also, the displacement and velocity of a servo actuator will be measured by sensors, then the values will be converted into signal by the F/V converter and signal conditioner, and will be utilized as feedback to compensate the error.
Figure 7 shows the control algorithms of a lever system

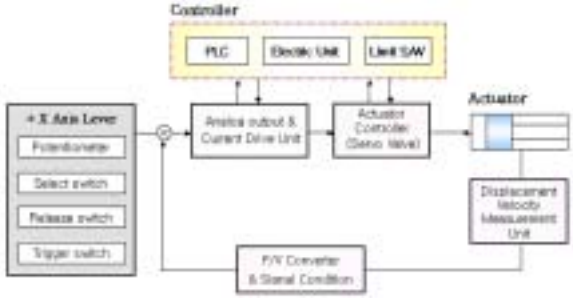

Figure 7. Algorithms of a lever system

4. Experiment for Optimal Spray Condition

4.1 The Objective of the experiment

The objective of this experiment is to examine the basic performance of manufactured equipment as well as to obtain basic data for the optimal spray condition, such as the spray distance, spray angle and injection pressure, to remove the road markings without damage before applied to the work in the field.

4.2 Experimental method and result

The total experiment accomplished under the atmospheric pressure and normal temperature with a 1-hole nozzle of 0.2 mm diameter. The specimen was manufactured in the size of 30cmX30cm, applied the paint in thickness of 2mm after dilution depending on the respective specs and dried for one week or more.
Table 1 shows parameters and conditions for the experiment.

Table 1. Experimental condition

Parameter	Conditions
Spray distance	10, 20, 30, 40, 50, 60, 70, 80 mm
Spray angle	30, 60, 80, 90°
Injection pressure	1,000, 1500, 2,000 bar
Working Fluid	Water

① Spray distance

The test method is as follows: First, the spray angle was fixed in 90 degree, and the injection pressure in 1,000 bar, the transfer velocity for a nozzle in 240mm/min. Second, the distance between a nozzle and a specimen alters from 10mm to 90mm in 10mm intervals.

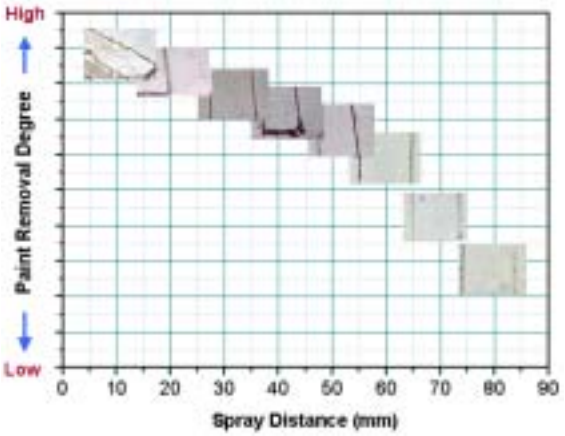

Figure 8. Result by variation of spray distance

The qualitative test result is shown in Figure 8. At the distance range of 10~20mm, there is the damage to take off the asphalt as well as road markings, on the other hand, at 70~80mm, the road markings was not removed perfectly. In conclusion, it can be realized that the optimal spray distance in current condition is at 40~60mm

② Spray angle

The test method is as follows: First, the injection pressure was fixed to 1,000 bar, the transfer velocity for a nozzle in 240mm/min. Second, the spray angle altered to the 30, 60, 80 and 90 degree. As shown Figure 9, a nozzle is fixed at the device, and the incline angle of specimen on the bed is altered. Figure 9 shows the test apparatus for altering the spray angle.

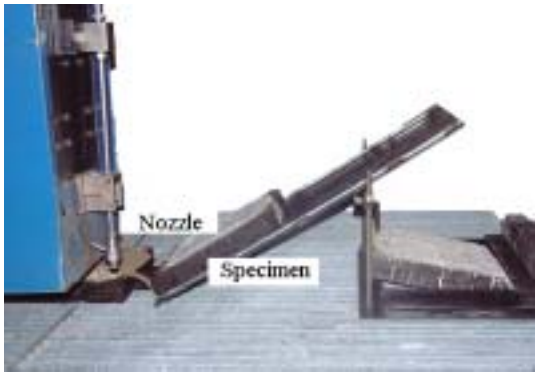

Figure 9. Test apparatus for the spray angle change

Figure 10 shows the experimental result in the case of different spray angle. Though the degree of removing is some qualitative, the spray angle at least should be 60 degree or more.

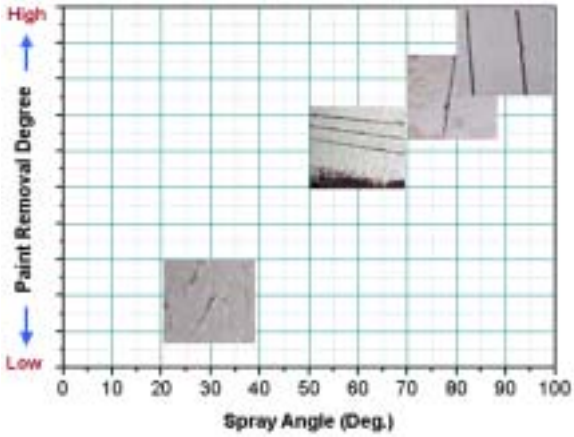

Figure 10. Result by variation of spray angle

③ Injection pressure

The test method is as follows: First, a 1-hole nozzle was made to reciprocate by using a rotational link and a servo motor while transferring in width direction simultaneously. Second, the spray distance was fixed to 20mm, the spray angle in 90 degree, the transfer velocity for a nozzle at 240mm/min, the rotation speed of rotational link mechanism with 500 rpm, and injection pressure altered to 1000, 1500, and 2000 bar.
Figure 11 shows the rotational link mechanism.

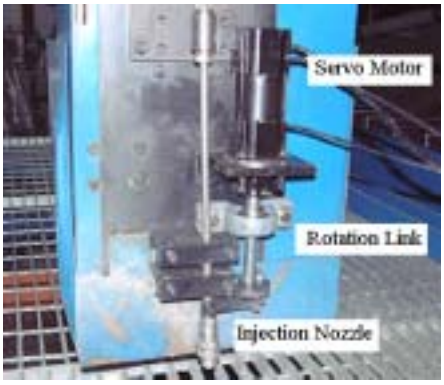

Figure 11. Rotational link mechanism

Figure 12 shows the experimental result in the case of different injection pressure. When water was injected with the pressure of 1,000 and 1,500 bar, the paint was not removed perfectly. It can be realized that the injection time is not sufficient but short due to quick reciprocating velocity. On the other hand, in 2,000 bar, the paint and even the asphalt of 1~2mm thickness were removed. In this condition, it is seemed that the injection pressure of 1700~1800 bar will be optimal.

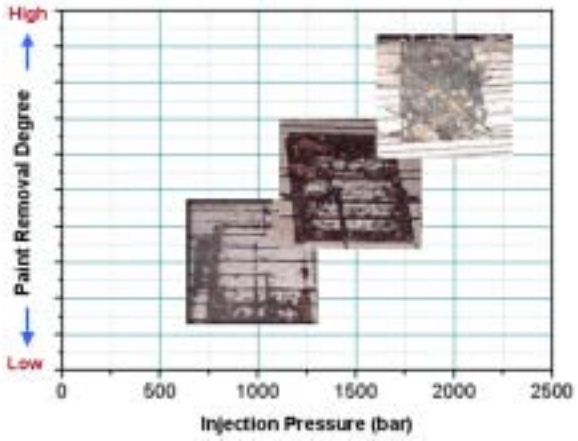

Figure 12. Result by variation of injection pressure

5. Conclusion

In this paper, for the development of the fast, safe, automatic and environmentally safe way to remove the road markings without damaging the surface by using water-jet, first of all, various analyses on the current shaving type removing method and work process through a field research were carried out. And, in the basis of these results, the whole system including each component have been organized and designed. Also, in order to examine the basic performance of manufactured equipment and to obtain basic data for the optimal spray condition, the basic experiment has been accomplished. In the future, after more detailed designs and system manufacturing, the performance on each components and the whole system will be evaluated, and the economic efficiency and marketability will be also analyzed.

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DYNAMIC PREDICTION MODEL FOR FINANCIAL DISTRESS IN CONSTRUCTION INDUSTRY USING DATA MINING

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Abstract

The early awareness of a potential financial distress is crucial to firm's managers for understanding their clients, suppliers and their own firms, and crucial to fund suppliers for assessing the construction firm's credit worthiness. The purpose of this paper is to develop a dynamic prediction model for financial distress in construction industry using Data Mining. This research expects to provide construction firm managers and creditors an effective index for evaluating the credit risk a construction firm. Results show that the proposed model has higher accuracy and stability for distress prediction and can provide a more effective quantitative framework for evaluating the financial standing of a construction firm.

Keyword: Financial Distress, Distress Prediction, Data Mining, CART (Classification and Regression Tree), Construction Industry.

1. INTRODUCTION

The early awareness of a potential financial distress is crucial to firm's managers for understanding their clients, suppliers and their own firms, and crucial to fund suppliers for assessing the construction firm's credit worthiness. Researchers have been trying to build effective financial distress prediction models by applying various approaches. The purpose of this study is to develop a dynamic prediction model for financial distress in construction industry using Data Mining.

Data Mining is one of the decision support technique for knowledge discovery. One of the classification algorithms is Decision Tree technique. This study expects to use the CART algorithm (Classification and Regression Tree) to build the financial distress predict model, and build the rules that can identify those companies that are highly possible to encounter financial distress.

2. LITERATURE REVIEW

Traditionally, the prediction of corporate failure relied on financial ratio analysis and there was no theory on how or when financial distress will occur. Bankruptcy prediction models were pioneered by Beaver's (1966) univariate test and Altman's (1968) multivariable discriminant analysis. Both studies show that financial variables can be used to predict bankruptcy. Since then, the prediction of corporate failure has been a topic of much interest. Recent works have extended this line of research into four directions: 1. utilizing different techniques, 2. examining the relationship between various definitions of bankruptcy and prediction models, 3. exploring a greater variety of explanatory variables, and 4. studying financial distress in particular industry. For example, in first direction, Tam and Kiang (1992) use one of the data mining classification techniques -C4.5 to estimate the probability of bankruptcy. In the second direction, Poston, Harmon, and Gramlich (1994) assign firms into one of three groups in financial distress according to each firm's financial condition: turnarounds, business failures, and survivors. They find that financial ratios are not so useful in distinguishing between financially distressed firms that are able to turn around and those that are unable to avoid failure. In the third direction, Rose and Giroux (1982) examine 28 business cycle indicators and find that economic conditions affect the failure process.

In the fourth direction, as suggested by Altman (1993), the characteristics of different industries are considered in the distress prediction models. Keasey, K., and McGuinness, P. (1990), Kangari, R., Farid, F., and Elgharib, H. M. (1992), Langford, Iyagba and Koma (1993), and Abidali and Harris（1995）are all focus in construction industry to build the financial distress prediction models.

3. METHODOLOGY AND DATA

3.1Method

Data mining has no particular assumptions on sample data, such as the normal distribution assumption in discriminated analysis. Decision tree is a typical classification tool for data mining. Whereas most decision trees algorithms have the same structure, various algorithms such as CHAID, C4.5/C5.0 and CART produce trees that differ from one another in the number of splits allowed at each level of the tree, how the splits are chosen when the trees are built, and how the tree growth is limited to prevent over-fitting. The fact that software packages often allow the user to choose a splitting criterion reflects that there is no single best choice for all problems. Data mining must experiment so as to determine which one gives the best results for the data set in hand.

CART (Classification And Regression Tree) algorithm is one of the main types of decision trees. Each branch of a decision tree is a test on a single variable that cuts the space into two or more pieces, and each split in this algorithm is constrained to be binary. The process for building decision tree is called recursive partitioning, an iterative process of splitting the data up into partitions. The algorithm chooses the split that partitions the data into two parts that are "purer" than the original. This splitting or partitioning procedure is then applied to each of the new boxes/categories. The process continues until no more useful splits can be found. So, the heart of the algorithm is the rule that determines the initial split.

The measure used to evaluate a potential splitter is the increase in purity. Purity represents the correct rate in the node, measured by Gini index (Berry, 2000). It can be interpreted as the probability that any two random elements of the population will belong to different classes. Since the probability index is simply one minus the sum of the all the Pi^2. The formula for the diversity index for binary targets is 2 P_1 (1-P_1), where P_1 is the probability of class one. It has been shown that the Gini criterion tends to favor splits that isolate the largest class in one branch of the tree.

3.2Sample and Data

The sample is from firms listed in the Taiwan Stock Exchange Corporation (TSEC) during 1985 to 2004. Financial distress is defined in this study as firms that either (1) were closed down by government authorities (all of which were banks and finance companies) or (2) were required by the Bank of Taiwan or TSEC to submit restructuring plans.

There were 76 firms listed in the TSEC, of which 31 were financially distressed by this definition. Firms' seasonal financial data were collected and each set of data from seasonal report is considered as one sample. As a result, total sample database consists of 1576 non-financially distressed samples and 495 financially distressed samples.

We choose the split points are 1995 to 2002, that partitions the data into two parts. Forward part data is training data set, and test data set is behind. The number of total database is 144. Several studies, for example, Beaver and Merwin (1966), indicate that firms may begin to exhibit the tendency toward failure as much as five years prior to the actual failure. Little is mentioned, however, of the actual significance of these early signs of distress. As Altman (1968) states: "Is it enough to show that a firm's position is deteriorating or is it more important to examine when in the life of a firm's does its eventual failure?" Here we will consider the financial data as much as five years prior to the actual failure. The definition of class show is in Table 1.

Table 1. The delineation of Class

Model	Types of Classes
D1	Normal, Distress (0 to 1 year before distress)
D2	Normal, Distress (0 to 2 years before distress)
D3	Normal, Distress (0 to 3 years before distress)
D4	Normal, Distress (0 to 4 years before distress)
D5	Normal, Distress (0 to 5 years before distress)

3.3Research design and Procedures

Considering the sample Choice-Based Biases and the sample Selection Biases (Zmijewski, 1984), we use all of the usable data. To detect financial distress, we set the null hypothesis, H_0, as "Distress," and we develop rules for identifying Normal firms. If a firm is identified as Normal, then H_0 is rejected and the firm is considered as Normal, otherwise, the firm is considered as Distress. However, when the firm is considered as Normal when H_0 is rejected, there is the type I error that H_0 is mistakenly rejected. As a result, type I error also means that a Distressed firm is considered as a Normal firm. Thus, the type I error (α) can be measured by the ratio of misjudgment through the rules developed for identifying the Normal firms. The procedures in this study for developing the financial distress models are as follows:

Step1. Data search and collect. We use the financial data from the TSEC, period ranging from 1985 to 2004. We also use the corporate basic data to build the class in Taiwan Economic Journal Data Bank (TEJ Data Bank).

Table2. Financial Variable

ROA-EBIT (%)	YOY-Total Assets% (Year-on-year growth)
ROE-NI (%)	YOY-Total Equity%
ROE -NI Exclude Disposal%	YOY-Fixed Assets%
Gross Margin (%)	YOY-ROA%

Realized Gross Profit%	Retention Ratio
Operating Income (%)	Current (%)
Pre-Tax Income (%)	Acid Test (%)
Net Income (%)	Interest Expense (%)
Non- Operating Inc./Revenue (%)	Debt/Equity (%)
Net Income%	Liabilities (%)
Operating Expense (%): Operating expense/ Revenue	Equity/TA (%)
CF-Operating CF/Current Liability (%)	(Long-term Liability+ Equity)/FA (%)
Interest Exp/Debt (%)	Interest-Bearing (%): debt/equity
PS(per share)-equity	Times Interest Earner
PS-Cash flow	Operation Income/Capital
PS-Sales	Pre-Tax Income/Capital
PS-Operating Income	Inv.& A-R/Equity
PS-Pre_ Tax Income	Total Asset Turnover
YOY-Sales%	A/R&N/R Turnover
YOY-Gross Margin%	Days A/R
YOY-Realized GM%	Inventory Turnover
YOY- Operating Income%	Days Inventory
YOY-Pre-Tax Income%	Fixed Asset Turnover
YOY-Net Income %e	Equity Turnover
YOY-Ordinary Income %	Days-A/P Turnover
YOY- NI Ex Disposal%	Net Operating Cycle

Step2. Data preparation：This step includes cleaning noises and handling missing values. The tasks of cleaning noises include finding repeated data or wrong property of database, and reconditioning data. In this study, after we delete missing values and repeated data, we have 76 companies, and 2071 seasonal samples.

Step3. Data converting and data warehousing: This step includes the determination and converting of data type, and the building Data Warehouse using IBM DB2.

Step4. Model developing: This step is to build the prediction Model using the CART (Classification and Regression Tree) algorithm used by IBM Intelligent Miner. Since this model will be revised later, we shall call the model before revision the "Original Model." According to the argument test, the best prediction power occurs when the minimum sample size in a node is 5, and the maximum node correct ratio is 100%.

Step5. Model evaluation and revision: After considering the cost of misclassification, we build the Original model is revised according to the criterion of pruning tree. Then consider the problem for over-fitting, we build the Revised Model when the maximum node correct ratio is 80% in the model.

4. THE DYNAMIC PREDICTION MODEL

In the research design, we find that a split of 70-30 percent for training set and test set works well in our test. This result is same to Berry (2000). So, we use the year from 1985 to 2000 to be training data set, and year 2000 to 2004 to be test data set.

The prediction ability, (total correct rate) is about 89.64% in Original Model. But the depth of decision trees in the Original Model is too much. So, we consider the problem for over-fitting to build the Revised Model.

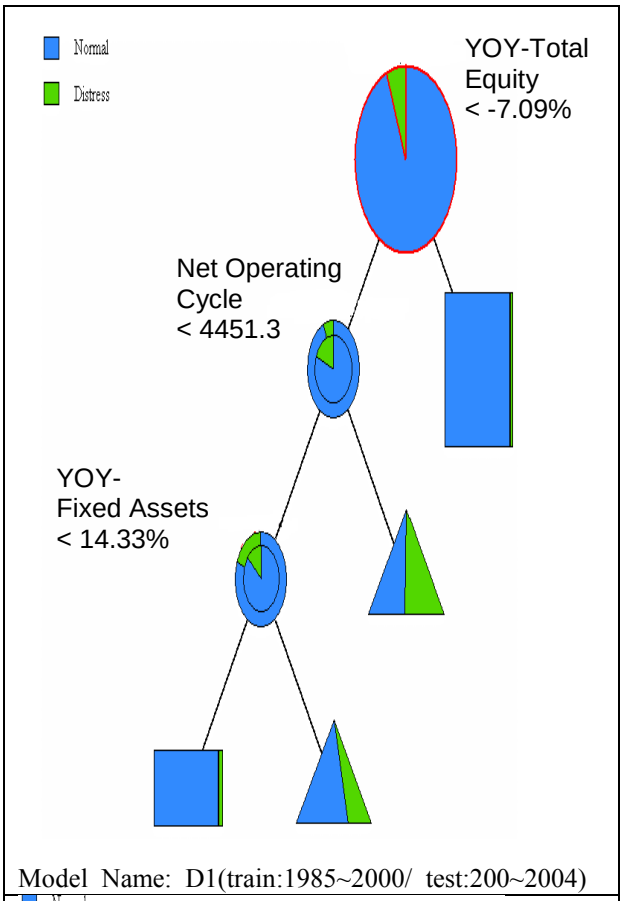
The prediction ability, (total correct rate) is about 73.93% in Revised Model. The performance of type I error in the four model (Original Training & Test Model, Revised Training & Test Model) is lower than 10%, and the type Π error rate is 53.78. Even we consider the long tern prediction result, the cost of misclassification is better than the literature (Altman, 1968). The performance of total minimum error rate, is the lowest in D1 model, the secondary is in D2 model. The error rate for Original Model and Revised Model is shown in table 3. The Revised Model rule is show in table 4.

Table 3.The performance for the Original Model and the Revised Model

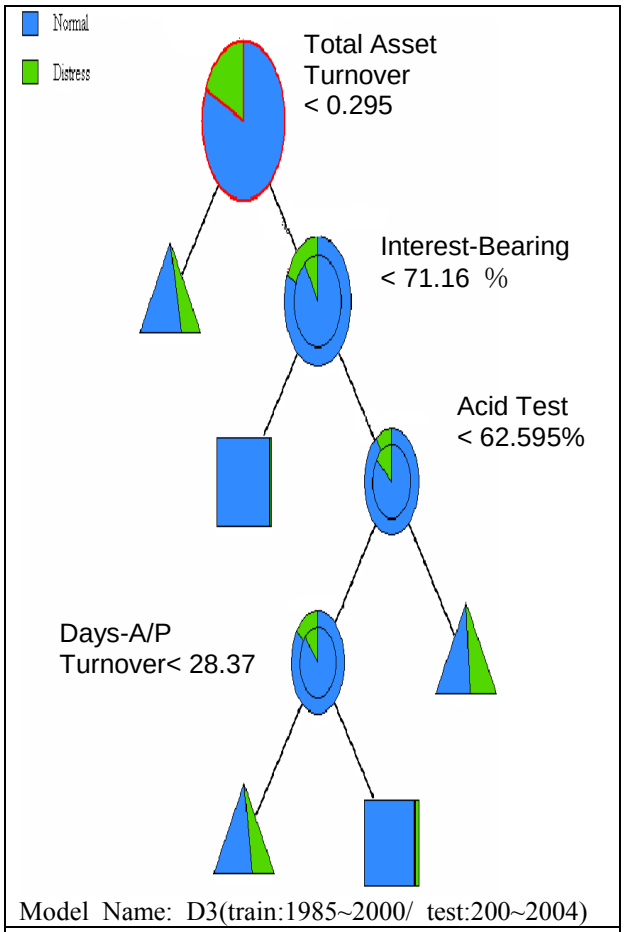
Model	Revised Model			Original Model		
	α	β	Total	α	B	Total
The error rate in Training Model (%)						
D1	3.3	62	6.2	4	17	4.9
D2	6	63	18.9	7	21	8
D3	8	69	35	7	20	9
D4	7	62	36	8	13	9
D5	7	65	44	8	16	10
The error rate in Test Model (%)						
D1	5.6	87	7.2	2	100	3.7
D2	2.5	82	18.4	4	69	7
D3	3	85	38	5	73	14
D4	9	65	20	7	72	18
D5	8	48	37	9	65	20

P.S. (1) Type I error: α (%) (2) Type Π error: β (%)

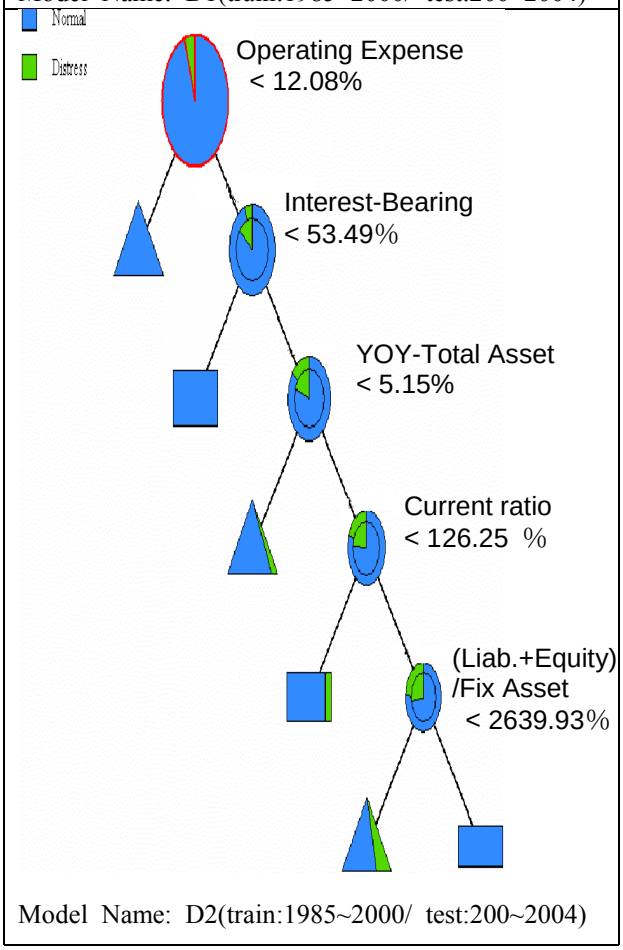
Table5. The Revised Model rule



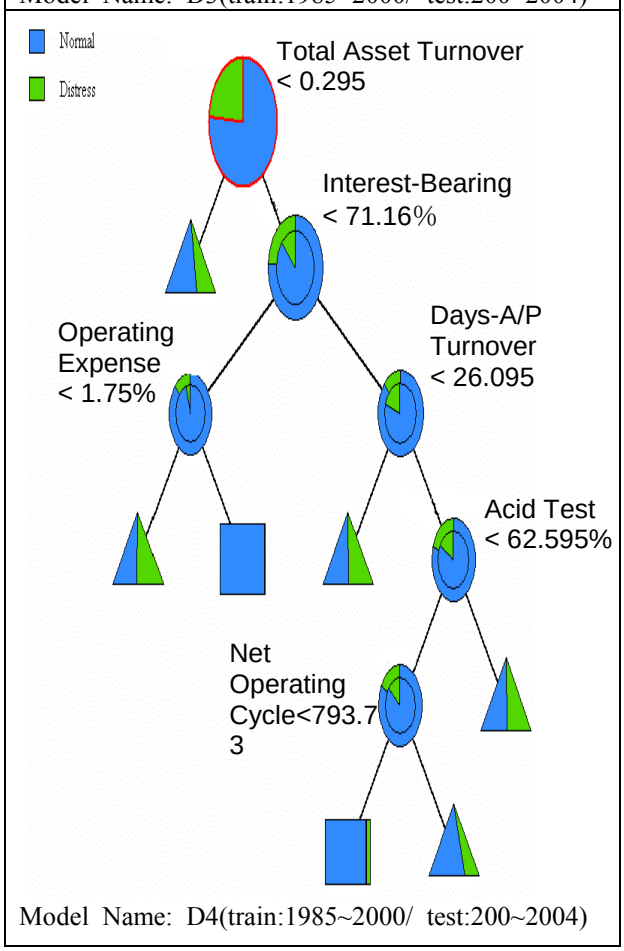
Model Name: D1(train:1985~2000/ test:200~2004)



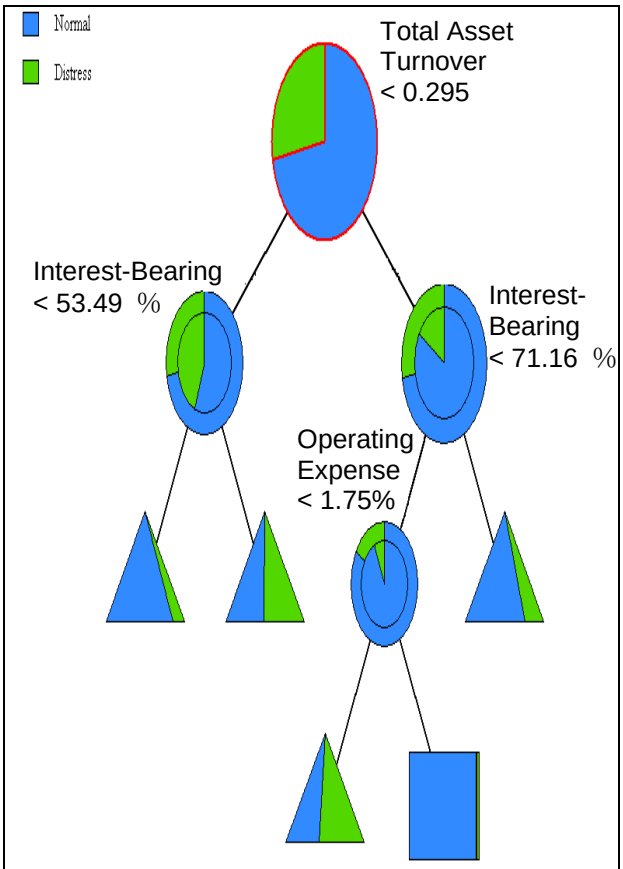
Model Name: D3(train:1985~2000/ test:200~2004)



Model Name: D2(train:1985~2000/ test:200~2004)



Model Name: D4(train:1985~2000/ test:200~2004)



Model Name: D5(train:1985~2000/ test:200~2004)

According to table 3, the most importance critical predicting variables are YOY-Total Equity%, Net Operating Cycle, YOY-Fixed Assets, Operating Expense, Interest-Bearing, YOY-Total Asset, Current ratio, (Liability +Equity) / Fix Asset, Total Asset Turnover, Days-A/P Turnover and Acid Test. Same of the variables same to the results by Abidali & Harris (1995) and Langford, Iyagba & Koma (1993).

Our models show that the Interest-Bearing(%) is the most important variables in differentiating between normal company and financial distress company. The suggested range of Interest-Bearing(%) in the short-term for a normal company is 53.49 % or so, and 71.16% in the long-term.And in long tern prediction ability, (3 to 5 years) Total Asset Turnover <0.295 occur to the financial distress company frequently.

Since current assets include inventory, if the current ratio is greater than 126.25%, the company may have too much inventory in hand, and as a result, the company may have higher probability of having financial distress.

5. CONCLUSIONS AND DISCUSSION

In this paper, we use all usable data as samples for minimum sample choice bias and apply CART algorithm to build the Original Model first and then revise it to the Revised Model. In the Revised Model, Interest-Bearing ratio and Total Asset Turnover ratio have great capability to differentiate between normal company and financial distress company. It shows that the construction company's profit is deeply affected by the problem for liabilities frequently. For creditor, we suggest you consider four years financial statement and use Revised Model–D1and D2 to predict financial distress company. If you have the data enough, you can use the Revised Model –D4 to predict the long tern performance of the company.

After consider the bias in literature, the overall predict correct rate is 89.64%. Then, we consider the problem for over-fitting to build the Revised Model. The prediction ability, (total correct rate) is about 73.93% in Revised Model. The performance of type I error in the four model (Original Training & Test Model, Revised Training & Test Model) is lower than 10%, better than the literature (Altman, 1968) and so on]. But the type Π error rate is 53.78. Perhaps the model performance is not very satisfied, but the predict result (1)is to be close to the fact ,(2) less uncertain than other model that didn't consider sample bias and(3)few cost of misclassification at least

In the research design, we have found a split of 70-30 percent for training set and test set works well in our practice. This result is same to Berry's research. [Berry, 2000]

For the follow-up researchers, we suggest you can use C4.5 algorithms to build the model, or use new variables, about industry characteristic, accede to the new models, to improve the model predict performance.

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A NEURO FUZZY SYSTEM FOR KNOWLEDGE DISCOVERY OF INCOMPLETE CONSTRUCTION DATA

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Abstract: This paper tackles problems encountered in mining of incomplete data for knowledge discovery of construction databases. As historical construction data are expensive to collect, any waste of incomplete data means not only loss of knowledge but also increase of costs for knowledge discovery of construction engineering. Unfortunately, incompleteness is commonplace in the existing construction databases. This paper proposes a VaFALCON (Variable-Attribute Fuzzy Adaptive Logic Control Network) neuro-fuzzy system that is equipped with the power for mining incomplete historical data. The proposed VaFALCON is shown to successfully mining of construction data with various percentages of missing attribute values.

Keywords: Construction; KDD; Data mining; Neuro-fuzzy; Incomplete data.

1. INTRODUCTION

The incompleteness, impurity, and scarcity of data are key problems confronting knowledge discovery in databases (KDD) of construction engineering and management. As historical data are valuable sources for KDD of construction knowledge, any waste of historical data can not only cause tremendous loss of valuable knowledge but also significant increase of costs for KDD of construction engineering. This problem is more serious while compared with similar problems in other industries due to two reasons: (1) the costs of construction projects are usually huge, thus it is expensive (if not impossible) to regenerate such data; (2) construction projects are unique in its nature, accumulating sufficient data for KDD has been a challenge in construction industry. Moreover, previous survey found that valuable historical data are not completely collected due to the uncertain nature of construction operations, the harsh environment of construction fields, and the attitude of construction staffs [1]. The incompleteness of data is commonplace in the historical construction databases. Unfortunately, rare traditional AI techniques, including numeric and symbolic reasoning schemes, are able to handle the incomplete data while performing data mining. Therefore, when some attributes information of historical construction data were missed, they are usually discarded. This causes another problem—data scarcity. The key reason is due to the disability of traditional data mining techniques in handling incomplete data.

This paper aims at developing a neuro-fuzzy system, based on the Fuzzy Adaptive Learning Control Network (FALCON) method [2], which is modified and improved so that it is able to handle historical data with missing attribute values. The proposed method is based on neuro-fuzzy system, so it is equipped with both learning and reasoning capabilities to mine construction knowledge from historical data. It also provides explanation of the reasoning process for system user to develop improvement strategy. Moreover, the proposed method modifies the learning mechanisms of the original FALCON with a special setup of data handling scheme. As a result, an variable-attribute learning scheme is developed. They can be used during the application. This is very useful for real-time decision making when the complete information cannot be acquired or when it is too expensive to collect.

This paper is presented in the following manner: at first, the FALCON neuro-fuzzy system is reviewed as a basis for methodology development in Section 2; the problem of data incompleteness in KDD is defined in the Section 3; the traditional approaches for handling incomplete data are described in Section 4; in Section 5, the proposed VaFALCON is introduced in details; in Section 6, two real world cases of incomplete data mining are demonstrated with the proposed VaFALCON method; finally, the conclusions and future works are discussed Section 7.

2. NEURO-FUZZY DATA MINING FOR CONSTRUCTION ENGINEERING

Construction engineering was conceived as an experienced-based discipline [3];, knowledge acquired from previous works plays a key role for

successful performance of the new projects. Not only the construction know-how of the contractors, but also the design capabilities of the design firms and the management skills of CM consultants rely heavily on such knowledge.

Today information technologies provides easy means to capture and store digitized data. With the computerization of construction industry, more and more of data have been collected and stored in databases. Even though the databases are promising sources for useful and valuable construction knowledge [4], the raw data are usually rarely of direct benefit. The true value of data resides in the ability to extract useful knowledge for decision-makers. When the scale of data manipulation, exploration, and inferencing exceed human capacities, it naturally prompts the need for intelligent data analysis methodologies, which could discover useful knowledge from data [5]. The emerging of KDD and Data mining (DM) techniques provides solutions for such need. The term KDD refers to the overall process of knowledge discovery in databases. Another related term, DM, is a particular step in the KDD process, which involves the application of specific algorithms for extracting patterns, models, or rules from data [6]. Among the many existing data mining algorithms, soft computing techniques (such as neuro-fuzzy systems) are most widely applied for a KDD process [6].

FALCON (Fuzzy Adaptive Learning Control Network) is one of the most successful development of soft computing techniques. It was first proposed by Lin and Lee for the purpose of automatic control [2]. It's then modified and enhanced by Yu and Skibniewski to automatic constructability knowledge acquisition [7]. Their research found FALCON provides many features desirable for construction knowledge acquisition including: (1) capability of handling uncertain information; (2) functions of learning; (3) explicit knowledge representation; and (4) trace-back functions for problem solving. An FALCON network consists of five layers of neurons: (1) input layer—taking input information; (2) input linguistic layer—transforming input information into fuzzy linguistic terms; (3) fuzzy rule layer—representing fuzzy IF-THEN rule base; (4) output linguistic layer—performing fuzzy inference process of fuzzy decision rules; (5) output layer—transforming fuzzy information to crisp decision information. The original FALCON model is shown in Figure 1. Details of FALCON computational algorithms are referred to Lin and Lee [2].

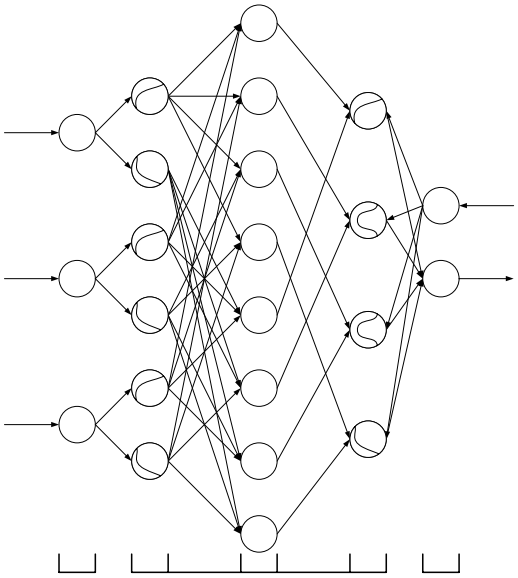

Figure 1. FALCON model [2]

3. DEFINTIONS OF INCOMLETENESS FOR CONSTRUCTION DATABASES

Incomplete data are commonly found in the traditional construction databases. Two categories of incompleteness are defined in this paper: (1) missing data—incomplete coverage of data in some intervals of the universe of discourse; (2) missing values—incomplete information in some interesting attributes. Following describes the problems of the two types of data incompleteness.

3.1 Missing data

The first type of data incompleteness problem is lack of data sets in some intervals of the universe of discourse for a specific attribute. This type of data incompleteness can be further classified into two categories: (1) interpolation type; (2) extrapolation type. For the interpolation problems, the data sets are missing between two clusters of data in the universe of discourse, see Figure 2. Thus, the missing data are usually recovered by interpolation schemes.

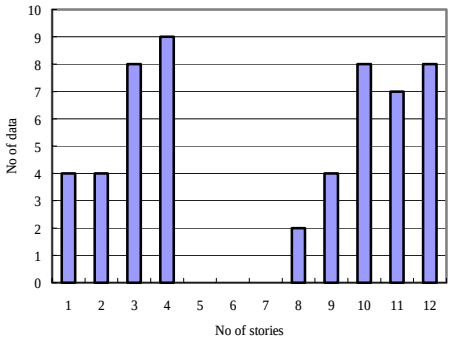

Figure 2. Interpolation type of missing data

On the other hand, for the extrapolation problems, the data sets are missing at extremes parts of the universe of discourse. Thus, extrapolation schemes are adopted for data recovery. Figure 3 shows an example of extrapolation type of missing data.

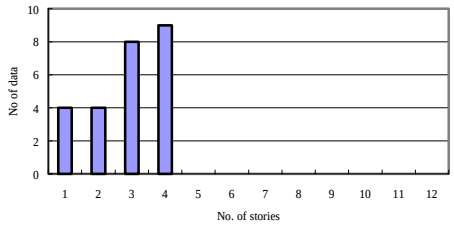

Figure 3. Exterpolation type of missing data

3.2 Missing values

In the second type of data incompleteness problem, some attributes of interest may not be available due to numbers of reasons: (1) the attributes are not considered important at time of data entry; (2) the mistakes made by collector; and (3) equipment malfunctions. This type of problem is more severe while merging databases from different sources. For example, in Table 1, data sources of firm A, B, and C provide inconsistent data format. The resulted database shows a typical example of missing-value type of data incompleteness, where the missing attribute values are depicted with shadowed cells.

Table1 Missing values in heterogeneous databases

Firm	weath.	Temp.	Humid.	item	Prod.
A	cloud	18			high
B		23	90%		low
C			60%	Form.	Ave.

3.3 Definitions of data incompleteness in this paper

This paper will tackle problems regarding to "missing values" rather than "missing data". That is, the incompleteness is defined as the percentage of unavailable attribute values. The missing data problem is not considered in this paper. In order to evaluate the degrees of incompleteness for missing values, two measures of data incompleteness are defined: (1) percentage of incomplete attributes (PIA)—measuring the number of unavailable attributes, which consist at least one missing value, over the number of total attributes; (2) percentage of overall incompleteness (POI)—measuring the total number of data set with at least one missing value over the number of total data set. In calculation of the above two measures of data incompleteness, only the precondition attributes characterizing a data set are considered, the consequence part of a data set, such as the last column (productivity) in Table 1, is not included.

4. TRADITIONAL METHODS FOR DATA CLEANING OF MISSING VALUES

There has been several methods proposed for filling in missing attribute values. Such methods are named "data cleaning". Han and Kamber proposed six methods for cleaning data with missing values [8]:

(1) Ignore the tuple—this method simply discards the tuple for all data. This is not a very effective, unless the tuple contains several attributes with missing values.
(2) Fill in the missing value manually—the method employs a domain expert to fill in the missing values based on his/her personal judgment. This method is quite straightforward and easy to implement. However, it is time consuming and sometimes error prone with bias of the domain expert.
(3) Use a global constant to fill in the missing value—this method replaces all missing attribute values with the same constant, e.g., "unknown". When "unknown" is adopted as the global constant, the problem is still unsolved for FALCON, since the "unknown" data is not acceptable for FALCON.
(4) Use the attribute mean to fill in the missing value—this method is similar to the previous one except that the global constant is replaced by global mean of the considered attribute. This method is a safer way for data cleaning. However, it is still biased.
(5) Use attribute mean for all samples belonging the same class as the given tuple—this method requires the user to classify the data first. However, this is sometimes impossible.
(6) Use the most probable value to fill in the missing value—this method employs some inferencing methods to recover the missing values, such as statistic regression, Bayesian formalism, decision tree induction, etc. This is possible the best, among the existing data cleaning approaches, for recovering missing attribute values. However, while the PIA or POI is high, this method may fail.

Considering the data mining process of FALCON, the traditional data cleaning methods are either limited in their capability or biased in their nature while handling missing attribute values. Moreover, when the ratio of missing values is high, all of the existing data cleaning methods tend to fail. It is therefore very desirable to develop a data mining technique that is able to handle data incompleteness problems regardless of the availability of domain experts and the severity of incompleteness.

5. THE PROPOSED VaFALCON APPROACH

This paper proposes a modified FALCON, namely Variable-Attribute Fuzzy Adaptive Logic Control Network (VaFALCON), for mining of incomplete construction data. The data incompleteness is defined previously as PIA (percentage of incomplete attributes) and POI (percentage of overall incomplete values). In order to improve the drawbacks of traditional data cleaning methods, the proposed VaFALCON aims at handling incomplete construction without restrictions on PIA and POI. Moreover, the proposed VaFALCON is designed to take incomplete construction data directly without data cleaning. Following describes the details of the proposed VaFALCON.

5.1 Mechanism of variable-attribute procession

Most of the current data mining techniques, including traditional FALCON and artificial neural networks, take only complete data without missing values as their inputs. While the input data are incomplete, data cleaning is performed to fill out the missing values. Therefore, the first step to develop VaFALCON is to establish a mechanism for processing variable numbers of attributes. Using the FALCON model in Figure 1 as a basis for discussion, there are three inputs (X_1, X_2, and X_3) and one single output (Y). Referring to Table 2, data set *A* is a complete data that consist of input and output pairs as ([a,b,c], D), where [a,b,c] is the vector of inputs and D is the value of output. The other incomplete data set $\bar{A}$ contains a missing attribute X_1 whose value is unknown and shown as "nan" meaning "not a number".

Table 2 Complete vs. incomplete data set

Attribute	X_1	X_2	X_3	Y
Data set *A*	a	b	c	D
Data set $\bar{A}$	nan*	b	c	D

*Not a number

The propagation of a complete data set in FALCON is shown in Figure 4, where the interconnections between the first two nodes in Layer 2 (pre-condition fuzzy linguistic terms) and Layer 3 (rule nodes) are shown as solid links, which means physical connections. As the first input (X_1) is missing, the resulted FALCON is shown in Figure 5. In Figure 5, the fuzzy linguistic term nodes of the first input (X_1) are disconnected (shown as dashed line) with the rule nodes in the following layer. The signals are not propagated via dashed-line links. In the traditional FALCON, the network of Figure 5 can not learn due to the undetermined links between Layer 3 and Layer 4.

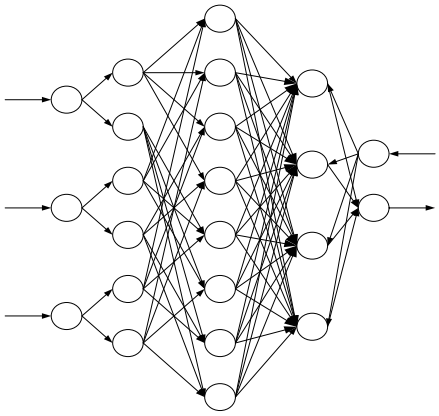

Figure 4. Connections of FALCON for complete data

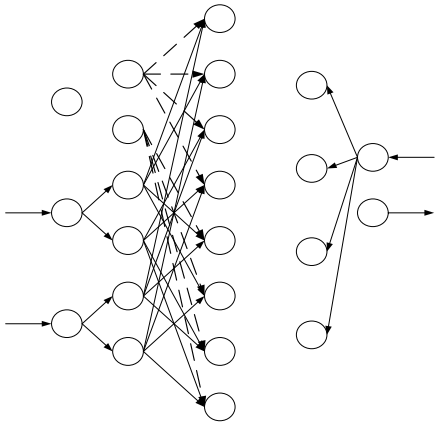

Figure 5. Connections of FALCON for incomplete data

Using the first principle of data cleaning described in Section 4, the first tuple (X_1) can be ignored while the information of the other two tuples (X_2 and X_3) are conserved. To make the best use of the data information, the FALCON is degraded as shown in Figure 6, where the first input is omitted. With the two residual tuples, the FALCON of Figure 6 can still learn from example data.

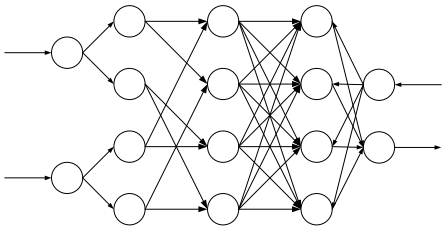

Figure 6. Degraded FALCON for incomplete data

5.2 Modified learning algorithms for VaFALCON

In order to implement the mechanism of variable-attribute procession for VaFALCON described in the previous section, the learning algorithms of traditional FALCON are modified as shown in the following.

(1) Modification of Kohonen learning rule

In order to take incomplete input data, Kohonen learning rule is modified as follows:

For means of membership functions—

if $x \neq nan$

$$\vec{w}_i^{k+1} = \vec{w}_i^{k} + \eta^k \left(x - \vec{w}_i^{k} \right)$$

$$\vec{w}_j^{k} = \vec{w}_j^{k} \quad , \quad \text{for } j = 1,2,...,n \quad j \neq i \qquad (1)$$

end

For spreads of membership functions—

if $x \neq nan$

$$\sigma_i = \frac{|m_i - m_{nearest}|}{\gamma} \qquad (2)$$

end

In both equation (1) and (2), "*nan*" (not a number) means missing of attribute value. The logic judgment in the first line of equation (1) and (2) represents that the modification is performed only when the attribute is not empty.

(2) Modification of *fuzzy AND* inference

The *fuzzy AND* inference of rule nodes in the third layer of FALCON performs t-norm computation, i.e., minimization or intersection. In VaFALCON, the goal is to avoid the situation that the memberships of the missing attributes become the outputs (i.e., minimum) of *fuzzy AND* operations. To achieve this goal, the memberships of missing attributes are replaced with the constant value "1.1" as shown in Table 3 and Table 4.

Table 3 Original outputs of Layer 2 in FALCON

Node	1	2	3	4	5	6
Output	nan	nan	0.825	0.236	0.148	0.567

Table 4 Modified input of Layer 3 in FALCON

Node	1	2	3	4	5	6
Output	1.1	1.1	0.825	0.236	0.148	0.567

After the modification described above, it is guaranteed that no missing attribute will become the output of *fuzzy AND* operations.

5.3 Learning process of VaFALCON

The learning process of VaFALCON consists of two phases: (1) Self-organizing phase—including modified Kohonen learning and reinforcement competitive learning to construct the primitive FALCON structure; (2) Back-propagation phase—applying back-propagation learning rule to fine-tune the network. The learning process ends when the expected error rate is achieved or the maximum number of learning cycles is reached.

6. SYSTEM TESTING

In order to demonstrate the power of the proposed VaFALCON, system testing is performed for two cases of real world construction problems: (1) mining data of building construction costs; (2) mining of duration data for slurry wall construction. The experiment is designed to compare the estimation accuracy of three scenarios: (1) learning of complete data set; (2) learning of data sets with various degrees of data incompleteness in terms of PIA and POI; (3) learning of incomplete data that discards the data sets with missing values. In the second scenario, the POI is set for 5%, 10%, 25% and 100%. The missing attributes are selected by a random process. The PIA for all cases in Scenario 2 is set to be 100%, that is at least one missing value is found in every tuple.

(1) Case I—mining data of building construction costs

In Case I, the historical data of building construction costs was collect from a research by Yu [8]. Totally 25 data sets were collected. Among those, 22 data are used for training and the rest 3 data are used as testing set. For Scenario 1 (complete data), the system accuracy is 94.66%. The accuracy of Scenario 2 and 3 for various degrees of POI are shown in Figure 7.

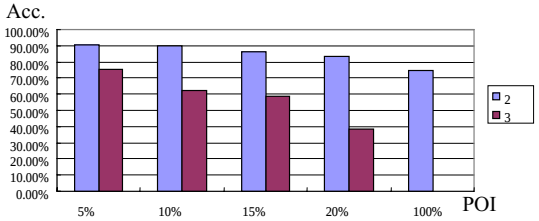

Figure 7. Comparison of accuracy between Scenario 2 and Scenario 3 for Case I

It is found from Figure 7 that the system accuracy of Scenario 3 decreases dramatically as the POI increase from 5% to 100%, while the system accuracy of Scenario 2 (with the proposed VaFALCON) decays moderately for the same degree of POI. As POI is 100% (i.e., every data in the training set consists at least one missing attribute), the proposed VaFALCON can still achieve system accuracy as high as 74.41%, while the Scenario 3 (discarding all data) cannot learn at all (system accuracy is 0%).

(2) Case II—mining of duration data for slurry wall construction

In Case II, the historical data of building construction costs was collected from a research by Yang [9]. Totally 27 data sets

were collected. 24 data are used for training and the rest 3 data are used as testing set. For Scenario 1, the system accuracy is 94.62%. The accuracy of Scenario 2 and 3 for various degrees of POI are shown in Figure 8.

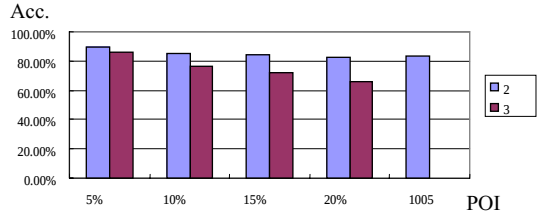

Figure 8. Comparison of accuracy between Scenario 2 and Scenario 3 for Case II

Similar results are found from Figure 8 that the system accuracy of Scenario 3 decreases dramatically in Case II, while the system accuracy of Scenario 2 is still high comparatively. As POI is 100%, the proposed VaFALCON can achieve system as high as 83.02%, while the Scenario 3 cannot learn at all (system accuracy is 0%)

From both of the above examples, it is concluded that the proposed VaFALCON can learn from incomplete construction data for various degrees of POI. It has significantly improved the traditional approaches of data cleaning in handling incomplete data. The improvement of system accuracy ranges from 14.98% (5% POI) to 74.71% (100% POI) for building construction costs and from 3.74% (5% POI) to 83.02% (100% POI) for slurry construction duration.

7. CONCLUSIONS AND FUTURE WORKS

This paper presents a proposed VaFALCON neuro-fuzzy data mining technique for knowledge discovery of historical construction databases. The proposed VaFALCON is capable of handling incomplete construction data. This feature is very desirable for construction industry, where data are scarce and data accumulation is expensive. Any waste of historical data may cause major cost increases for KDD. Moreover, due to the harsh environment of construction job site, incomplete data collection is nature in construction databases. The proposed VaFALCON can meet all of the above needs. It is found from the demonstration examples that the improvement of system accuracy range from 3.74% (5% POI) to 83.02% (100% POI), which verifies the value of the proposed VaFALCON method.

The proposed VaFALCON is able to handle incomplete data with missing attribute values, however the missing data problem discussed in Section 3.1 of this paper is still unsolved. Ambitious researchers are encouraged to pursue in that field.

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THE APPLICATION OF KNOWLEDGE MANAGEMENT IN TAIWAN CONSTRUCTION INDUSTRY

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Abstract: Knowledge management has already demonstrated a number of benefits and has offered justification for further implementation. The Internet facilitated its development and growth via fast and timely sharing of knowledge. By sharing knowledge, a enterprise can creates exponential benefits from the knowledge and experience as employee learns from it. In Taiwan, the construction industry is attempting to take a further step to apply knowledge management (KM) to capture, store, share, and reuse past information and knowledge in their projects. A survey is made to identify the application and problem of knowledge management in public sector and private sector in the A/E/C industries of Taiwan. This paper focuses on the current implementing and problem of the public and private sections in construction knowledge management. The purpose of the paper is helpful to further understand the strategy and problem solving for implementing construction knowledge management successfully. Finally, suggestions and strategies based on the survey are provided in the paper to help and apply the future implementing of knowledge management in the A/E/C Industries.

Keywords: Knowledge Management; Knowledge Sharing; Strategies; Construction Project

1. INTRIDUCTION

The construction companies in Taiwan are facing rising competitive pressure after the entry to WTO. On the other hand, government is launching Industrial Automation & Electronic Business Program for advance of the Electronic Business. Therefore, the construction industry (A/E/C industries) starts to apply information technology (IT) to improving their business process and efficiency of management in the purpose of enhancing competitive advantage such as ERP, SCM and KM systems.

As the growth of the computerized construction data, the construction industry begins to collect and store the data in the center repository. For the effective reuse of the data, the construction industry apply rate of knowledge management (KM) is arising. For the better understanding of this trend, a survey is made to identify the application and problem of knowledge management in public sector and private sector in the A/E/C industries of Taiwan. Finally, suggestions and strategies based on the survey are provided in the paper for the future implementation of knowledge management in the A/E/C Industries.

Scope of work

The scope of this research project included reviewing literature of KM and its implementation, investigating application of KM in Taiwan Construction Industry, and offering suggestions and strategies for the KM implementation. The scope of this survey is including public sector and private sector (A/E/C companies) in the purpose of investigating the Application of KM in Taiwan construction industry.

In addition, the survey was distributed to 2206 organizations among the construction industry in the entire island of Taiwan. A survey was used to reduce the time required while investigating comprehensive opinion.

The questionary used for this survey included for sections and 21 questions. The different sections were divide into (1) demographic questions about survey participants and the organizations they work for, (2) application of KM including percentage, situation and

problem of KM implementation, (3) the scope of KM implementation including types of knowledge and knowledge management system, (4) the expected benefits of KM implementation.

Of the 2206 questionaries was distributed, a total of 465 responses were returned. The response rate is 21%. Due to the space limitation, the article does not include the questionary. The paper focuses primarily on the responses obtained for each question.

2. LITERATURE REVIEW

The construction industry fragmentation is caused by (1) separate design and construction functions and (2) the specialization of designers and builders into more specific fields of operation [1]. And the project teams in the construction industry are temporary organizations involving individuals in several companies. Therefore, many individuals and companies are joining among the life cycle of any project and besides, the knowledge is distributed and lost at the end of project.

The primary benefit of KM for staff in organization is capturing and reusing knowledge to create knowledge and benefits. Specifically, reusing knowledge can lead to greater competitive advantage, reduce rework time, and act as a learning resource for novices [2]. However, KM is not homogeneous because there are two types of knowledge: tacit and explicit. According to Polanyi's definition tacit knowledge is highly personal, context-specific, and therefore hard to formalize and communicate [3]. Explicit knowledge refers to codified knowledge that is transmittable in formal, systematic language and is easily transferred by using IT [4]. And the different type of knowledge will lead different efficacy. Furthermore, AEC firms have been successful at collecting and storing explicit information in enterprise databases, but they are not always good at tacit knowledge retrieval and sharing[4]. This is because tacit knowledge is stored in the expert brain. In the construction industry tacit knowledge is very important for a novice. Usually, a novice asks a experienced workers or engineer in order to get the specific tacit knowledge. In the construction industry, finding the reusable item and exploring both its context and evolution history are the two key activities in the reuse process [2]. And the context is housed in the brain of experienced workers or engineer. Although tacit knowledge is very important for the construction industry, AEC organizations are often ignoring it for it's difficult to capture. In the other word, the AEC organizations adopt the explicit knowledge strategy. In the past studies, dynamic knowledge map [4] and community of practice (COP) [5] are helpful for the problem of the reuse of tacit knowledge. The term COP is defined as an informal network or forum where tips are exchanged and ideas generated [5].

Another typical strategy in the construction industry focuses on the knowledge management system (KMS). Actually, many of the AEC organizations in Taiwan only built a KMS for collect ing and storing explicit knowledge while they implement KM. However, the framework for organizational readiness for KM includes not only KMS (IT tools), but also organizational context such as metrication and culture [6].

But the IT tools such as KMS still play a critical role in KM process. KMS could be a substitute for face-to-face contact. Thus, KMS can reduce the time and geographical barriers that limit KM activities. And KMS could also be the knowledge repository in which knowledge is stored in the organization. The key is therefore to understand how technology is most appropriately deployed and aligned to the knowledge activities in the organization [7]. In the purpose of intending to bridge the gap between KMS and KM process, a three-tiered KMS architecture is proposed include presentation services (Two common features of presentation services are personalization and visualization), knowledge services (The two main infrastructure services provided by technology are storage and communication), and infrastructure services (The underlying knowledge processes of these three KM goals are knowledge creation, knowledge sharing and knowledge reuse) [7]. Besides the application of KMS, further IT application research includes: KDD（Knowledge discovery in databases）technologies that discover Predictable patterns that help manager to predict potential problems[8], and information retrieval algorithms that can support effective knowledge reuse[9] is developed for construction industry. And these technologies can assist in building effective and efficient next generation digital knowledge management environments.

3. SURVEY RESULTS

This section contains the result obtained from the data collected from questionaries that returned.

Demographic information

The survey results of the demographic information included company type and the years of employment of the respondents. The company type and its percentage were

- General contractor and specialty subcontractor (37.27%)
- Professional supplier (23.28%)
- Public sector (14.63%)

- Engineering/consulting companies (13.30%)
- Architect (8.42%)
- Other types of companies (3.1%)

The number and percentage of years of employment of the respondents were

- less than 2 years (4.90%)
- 2-5 years (19.15%)
- 5-10 years (22.05%)
- 10-20 years (38.08%)
- 20 years or more (15.81%)

The application of KM

The application of km obtained the implementation level of KM in the construction industry. The survey responses indicated that only 21.3 % of the respondents had already applied KM to their organization. Most of the respondents are on the stage of building or planning KM. The results of the responses were tabulated in Table 1.

Table 1. Implementation level of KM of the respondents

implementation level of KM	Percentage of respondents (%)
Already apply KM	21.3
Building of KM	20.4
Planning of KM	31.8
Not consider yet	26.5

The knowledge sharing ways

The survey obtained the information from the respondents about the knowledge sharing ways of the organization. And the major types were: ask coworker directly, training program, applying KMS, and meeting. The items and the percentage were

- No exchange/share (0.91%)
- Ask coworker directly (20.20%)
- Phone (8.92%)
- E-mail (10.06%)
- Meeting (18.67%)
- Study forum (1.45%)
- Conference (6.02%)
- Internet forum (3.05%)
- Training program (19.89%)
- Apply KMS (7.93%)
- E-learning program (2.29%)
- Others (0.61%)

Knowledge store methods

The survey obtained the information from the respondents about the Knowledge storing methods. And the major types were system archive, paper archive, and Store by the individuals. The results of the survey were shown in Table 2.

Table 2. Knowledge storing methods f the respondents

Knowledge storing methods	Percentage of respondents (%)
No Knowledge storing methods	1.46%
Store by the individuals	24.30%
Paper archive	22.51%
System archive	27.77%
Common IT repository	17.13%
KMS repository	6.61%
Others	0.22%

Difficulties of implementation of KM

The survey also asked respondents to identify the Difficulties of implementation of KM. And the results shown in the responses were in the following area:

- No systematically implementation (21.07%)
- Misfits of KMS (13.99%)
- No taxonomy of knowledge to refer (13.21%)
- No reward system for KM (13.21%)
- Current KM taxonomy is confusing (13.05%)
- No knowledge dissemination methods (8.81%)
- No knowledge extraction (8.65%)
- No COP (5.97%)
- Other (2.04%)

The content of knowledge demand in KM activities

The survey also obtained the information regarding the content of knowledge demand in KM activities. The responses from the respondents were in the following content

- Codes and Specification (CNS and ASTM)
- Applicable Law
- Standard Drawing
- Technic and Methods
- Material price

Application of KMS

The survey requested information about the Application of KMS, and the responses indicated that much of the respondents (61.72%) developed KMS by themselves. Furthermore, the survey also investigated the function that KMS provided. Table 3 shows the results.

Table 3. KMS function of respondents

Provided function	Percentage of respondents (%)
Knowledge content structure	18.81
Announcement Management	17.01
Automatically knowledge capture	12.24
Full-text retrieval	10.45
Automatically categorized	10.15
Group forum	8.36
Personalized assistant	7.46
E-learning	7.16
Multimedia supported	5.07
Knowledge Map	3.28

Expected benefit of KM

The survey also requested both the individual and organizational expected benefit of KM. The Likert-type Scale was use in the two questions of this section, and the scale was from 1 to 5. The responses and the average score were in the following.

Individual Expected benefit of KM
- Capture the needing knowledge rapidly (4.45)
- Learning experience from others (4.39)
- Enhance the efficiency of job (4.29)
- Accumulate personal knowledge rapidly (4.29)
- Facilitate knowledge sharing and reuse (4.27)
- Increase personal ability of recreation (4.18)
- Decrease mistakes (4.03)

Organizationally Expected benefit of KM
- Collecting and storing knowledge (4.20)
- Building consistent taxonomy (4.12)
- Enhancing organizational efficiency (4.12)
- Accumulate Organizational knowledge rapidly (4.11)
- Enhancing competitive advantage (4.06)

4. SURVEY ANALYSIS

The responses of the survey show that only 21.3% of the respondents had already applied KM. Among all types of the company, public sectors and Engineering/consulting companies had better application rate in 29.2% and 25%.

The interviewee uses two main methods to share knowledge: face-to-face and training program. Taiwan construction industry rarely utilizes the IT tool such as KMS or group forum for COP. Thus, the time and geographical barriers limit KM activities. The survey results indicated that of the organizations had already applied KM, 43.8% of the individuals will utilize the KMS to obtain knowledge than 31.5％ of the organizations that Building KM.

The results of the survey also show that most of the organizations are still storing knowledge by individuals and System archive. This will cause the dissemination problem of knowledge because it is not easy to obtain the knowledge.

Two main issues about the difficulties of implementation of KM are identified as the KM issue and the organization issue. KM issue includes No systematically implementation and Misfits of KMS. In Taiwan construction, KMS often take as a quick solution to implementing KM without helping from KM consultant. The survey results also show that most KMS developed by technologists are not well integrated into the construction industry process. On the other hand, 61.7% of the responses decided to develop their particular systems; however, most of those systems were not well designed. The major functions provided by KMS developed by technologists and AEC organizations focus on Knowledge content structure, Announcement Management, Automatically knowledge capture, and Full-text retrieval. Based on the responses , the paper identified KMS functions applied in the respondent organization focus on categorizing and capture knowledge. According to the literature mentioned above, there were some failures in the following: (1) communication function such as collaboration and group forum of COP, (2) Knowledge Map (K-map), (3) learning function such as E-learning and multimedia supporting.

Organization issue is the lack of KM reward system. Past studies and practice discover that reward system is very important for implementation of KM. Since Taiwan construction industry doesn't emphasize on reward system, the tacit knowledge is difficult to capture in that employee do not want to share it considering personal competitive advantages.

The information regarding the content of knowledge demand obtained from the respondents show that KM strategy of Taiwan construction industry is explicit knowledge strategy. Compare with Individual Expected benefit of KM, the demand of tacit knowledge is not matched. Consequently, individuals must obtain tacit knowledge by face-to-face way instead of utilizing KMS.

5. RECOMMENDATIONS

Based on the survey results and analysis, the suggestion and strategies for KM implementation of Taiwan construction industry offered:

(1) The strategy of knowledge should include both explicit and tacit ones.

(2) The knowledge-distributed condition should be improved and utilized Web-based technology to improve the access of knowledge.
(3) Reward system is important to KM, especially to the capture of tacit knowledge.
(4) COP and group forum can help the dissemination of tacit knowledge.
(5) KMS should add more function such as communication, K-map, and learning function.

6. CONCLUSIONS

Taiwan construction industry has a consensus about benefit of KM. Based on the survey and past studies, the implementation of KM need to improve for better benefit of reuse knowledge.

The tacit knowledge strategy must be emphasized in the purpose of individually expected benefit, of enhancing the working efficiency, and advance of knowledge repository. The sharing and reuse of knowledge can also be improved through the tacit knowledge strategy. Thus, the application of well-developed KMS can decrease the time and geographical barriers limit KM activities. Consequently, KM can really lead to greater competitive advantage.

The suggestion for future research is the implementation process of KM should be addressed since the paper has discussed the benefits and strategies of KM for Taiwan construction industry. Furthermore, the culture issue has not included in the scope of the survey needs to be addressed for clarifying how culture affect. Research on the new IT application and its benefit are also needed for the KM.

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SCHEDULE MANAGEMENT PROCESS MODEL BASED ON CSDM

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Abstract: The duration of a construction project must be an important item in construction contracts. If a contractor can work in the planned parameter, the contractor can finish the construction project in a timely manner. However, when construction industry is compared to other industries, it is difficult to complete a construction project in which many construction trades participate during the construction phase. In most cases, there are numerous impact factors that impact a construction process and hinder its timely completion. Those impact factors can be categorized construction schedule risk, productivity, constraints and so forth. The scheduler must consider the impact factors to plan the construction project schedule. But, many studies or methodologies or programs on planning the construction schedule have been focused on the result of works. So, this study proposes the schedule management process model based on CSDM (Construction Schedule Data Mart) considering data warehousing, MOLAP (and case-base reasoning.

Keywords: CSDM(Construction Schedule Data Mart), Schedule Process, Impact Factor, Schedule Risk, CBR(Case-Based Reasoning)

1 INTRODUCTION

The duration of a construction project must be an important item in construction contracts. If a contractor can work in the planned parameter, the contractor can finish the construction project in a timely manner. However, when construction industry is compared to other industries, it is difficult to complete a construction project in which many construction trades participate during the construction phase. In most cases, there are numerous impact factors that impact a construction process and hinder its timely completion. Those impact factors can be categorized construction schedule risk, productivity, constraints and so forth. So, the scheduler must consider the impact factors to plan the construction project schedule. But, many studies or methodologies or programs on planning the construction schedule have been focused on the procedure and the result of works. This study focused on the process of construction schedule management instead of the result of construction project. This study involves all of the construction schedule management during planning and construction.
So, this study proposes the schedule management process model based on CSDM(Construction Schedule Data Mart) considering impact factors and case-based reasoning.

2. PROCESS MODEL OF SCHEDULE MANAGEMENT

2.1 the objective of schedule management

The objective of schedule management is exteriorly to succeed the construction project during the contracted construction project period and internally to do organizational own effort within limited resources such as cost, material, machine, labors, method etc., to meet the contracted period. The organization structure of schedule management is shown in fig.1. It is important to cooperate systematically the schedule management of the horizontal-vertical organization.

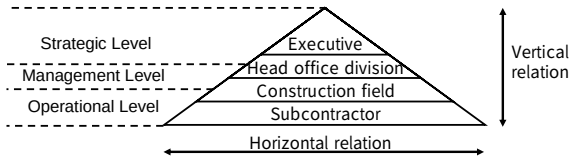

Figure 1. Organization structure

The work scope and decision items are different according to the level as follows.
(1) Strategic level : making schedule management strategy according to the company's strategy.
(2) Management level : supporting the operational level and making the workable construction situation.
(3) Operational level : making more workable construction situation than management level, checking the work process and outcomes, performing the work, comparing the work performance with work schedule and reflecting the difference of work performance and work schedule to the following work plan, making a schedule meeting and so forth.

2.2 project planning

Project plan is the function of selecting the enterprise objectives and establishing the policies, procedures, and programs necessary for achieving them. Project planning must be systematic, flexible enough to handle unique activities, disciplined through reviews and controls, and capable of accepting multifunctional inputs (Kerzner(1998)). Project plan is the document for the project work involving all works from the start of project to the component of the future works. Popescu and Charoenngam (1995) described the project planning and control cycle in fig.2.

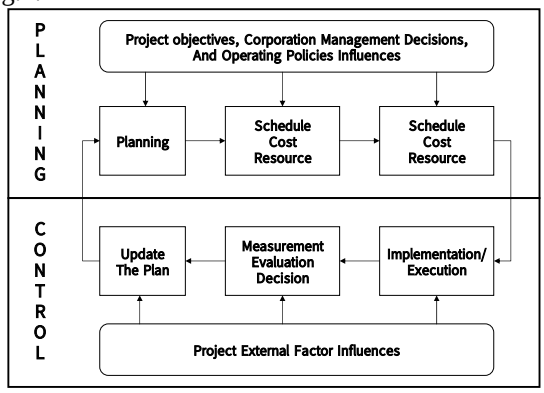

Figure 2. Project planning and control cycle

Construction project is the dynamic entity to be actively managed to the internal and external conditions. The construction project schedule plan is composed of project planning and control considering such dynamic conditions. As shown in fig.2., project planning is made based on operation' strategy and objective of the project management. The project planning are controlled during implementation/execution, measurement, evaluation, and feedback considering project external factor influences.

Table 1. shows the project planning objectives and the means to the objective.

Table 1. Project planning objectives and means

Project planning objective	Means
Requirement confirmation, Service order confirmation	·contract review and implementation ·time cost trade-off decision ·master plan
Owner's special requirement confirmation	·contract review and implementation
Work scope and flexible relation structure establishment	·quaterly, monthly, and weekly schedule
Resource allocation efficiency	·resource allocation plan
Responsibility, authority, work relationship establishment	·contract review ·construction plan
Work planning form confirmation	· making operation's standard form and manual
Consensus of opinion, Making participant's responsibility	·contract review ·schedule meeting
Making detail drawing	·specification ·operation's standard
Time control	·performance measurement ·work control and feedback
Information gathering method	·input and output information definition

Table 2. shows the project control objectives and the means to the control.

Table 2. Project control objectives and means

Project control objectives	Means
Comparing work performance with work plan	·performance graph
Verification of optimal work pattern	·verification of maximum productivity
Decision of specific work pattern	·reschedule
Recovery time	·acceleration or delay and so forth.

4. IMPACT FACTORS ON DURATION AND THE UTILIZATION OF CSDM

4.1 CSDM (construction scheduling data mart)

Construction schedule data and information can be managed through the network between server and client. Fig.3. shows the life cycle of the CSDM (construction scheduling data mart).

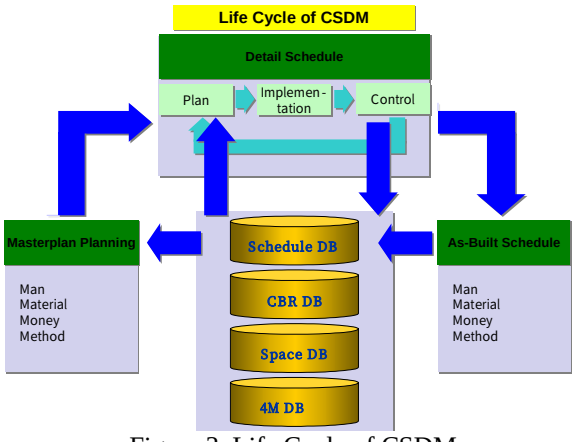

Figure 3. Life Cycle of CSDM

Construction schedule master plan is drawn before construction by using the accumulated information of the CSDM, the detail construction schedule is drawn during construction and confirm the work performance. The accumulating process of the schedule related information is repeated periodically as a quarter, month and week. After completion of

the construction project, the construction schedule related information is accumulated for the using of the following similar project scheduling.

4.2 system structure of CSDM

The schedule related information is accumulated from the company's operating system such as ERP, PMIS, daily report system, construction schedule system to database of the CSDM through ODS(operational data store). The ODS serves as a point of integration for operational systems. In many cases, these ODS are implemented to better support one-to-one customer relationships in the order entry or customer service function. The ODS should be a subject-oriented (schedule-oriented in this study), integrated, frequently updated store of detailed data to support transaction systems with integrated data. Any detailed data used for decision support should simply be viewed as the lowest atomic level of the data warehouse.

The cumulated information of CSDM can be used through CBR (Case-Based Reasoning) and MOLAP (Multidimensional On-Line Analytical Processing) to make a schedule related decision. Fig. 4 shows the system structure of CSDM.

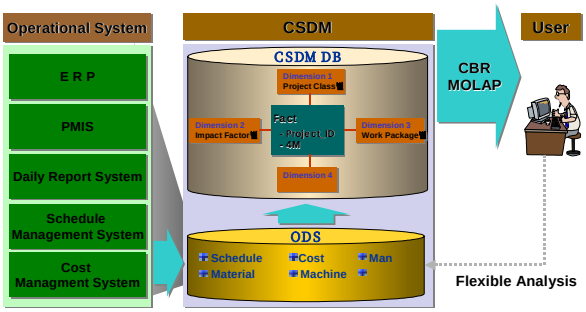

Figure 4. System Structure of CSDM

4.3 MOLAP

Kimball (1998) described that MOLAP (Multidimensional On-Line Analytical Processing) is a set of user interfaces, applications, and proprietary database technologies that have a strongly dimensional flavor. Since the MOLAP tools were built for decision support, they tend to have much stronger analytical functions built into the engine. Some of the MOLAP tools allow both reads and writes to the data, which makes them very important for applications like schedule forecasting. MOLAP engines, also known as multidimensional database management system, are database management systems that are designed to provide specialized support for dimensional analysis such as project class dimension, impact factor dimension, work package dimension and so forth. MOLAP engines can make an excellent data mart platform for schedule related requirements that can be met by a fairly simple star schema-that is, relatively few dimensions, each with relatively few rows. The most significant benefits of using a MOLAP engine is the end user query performance. Facts are prestored at all valid combinations of the dimensions.

5. PRECONSTRUCTION PLANNING BY USING CBR

5.1 the usage of CBR (case-based reasoning)

CBR can be regarded both as a cognitively sound modeling approach for explaining human problem solving in domains where experience plays an important role (Strube and Janetzko (1990)). It is especially appealing to those professionals who solve problems by recalling what they did in similar situations that happened in the past. The basic idea of CBR (case-based reasoning) is to adapt solutions that have been used to solve old problems for use in solving new problems (Turban and Aronson (2001)). A case is the primary knowledge-base element in a case-based reasoning application. It defines a situation or problem in terms of natural language descriptions and answers to questions and associates with each situation a proper business action. Scripts can be constructed from historical cases that reflect human experience. The experience can be that of the decision makers or of others. CBR is the essence of how people reason from experience. CBR has been proposed as a more psychologically plausible model of the reasoning of an expert than a rule-based model. A theoretical comparison of the two was made by Riesbeck and Schank (1989), and a summary is provided in Table 3.

Table 3. Comparison of Case-based and Rule-based Reasoning

Criterion	Rule-based Reasoning	Case-based Reasoning
Knowledge unit	Rule	Case
Granularity	Fine	Coarse
Knowledge acquisition units	Rules, hierarchies	Cases, hierarchies
Explanation mechanism	Backtrack of rule firings	Precedent cases
Characteristic output	Answer and confidence measure	Answer and precedent cases
Knowledge transfer across problems	High if backtracking; linear if deterministic	Low
Speed as a function of knowledge base size	Exponential if backtracking; linear if deterministic	Logarithmic if index tree is balanced
Domain requirements	Domain vocabulary	Domain vocabulary
	Good set of	Database of

	inference rules	example cases
	Either few rules or rules apply sequentially	Stability (a modified good solution is probably still good)
	Domain mostly obeys rules	Many exceptions to rules
Advantages	Flexible use of knowledge	Rapid response
	Potentially optimal answers	Rapid knowledge acquisition Explanation by examples
Disadvantages	Computationally expensive	Suboptimal solutions
	Long development time	Redundant knowledge base
	Black-box answers	

CBR has proved to be an extremely effective approach in complex cases (Kolonder (1993)). According to Riesbeck and Schank (1989), the basic justification for the use of this approach is that human thinking does not use logic (or reasoning from first principles).

More over, CBR has been used to create numerous applications in a wide range of domains, including financial analysis, risk assessment, technical maintenance, process control, quality control, medical diagnosis, software support systems, forecasting, planning, design, classification of objects, photo-interpretation, and real estate appraisal (Althoff and Bartsch-Spörl (1996))

Likewise, many human schedulers create schedules by reusing past similar schedules (Dzeng and Tommelein (2004)). It is difficult for a human project planner to newly generate a project network without referring to any previous cases because the amount of required knowledge is too large and complex. Therefore, human experts usually look for a similar previous project network for reference and get previous human expert knowledge by referencing previous similar networks (Lee et al (1998)).

The retrieval and reuse of similar schedules are subjective and experience-based. Constructing a new schedule is a matter of finding suitable network fragments from previous schedules and adapting these for reuse. Traditional scheduling tools provide only limited features to facilitate such reuse . For example, Primavera Project Planner (P3 (1999)) allows the user to define and reuse the fragnet, a subnetwork composed of activities with fixed names, duration, and sequential relationships between each other. A limitation of P3 is that the fragnet has no relationships with the data pertaining to the project it was initially created for, and can be retrieved only by its name. Modification of the fragnet may be required before it is used. P3 provides features that facilitate the addition of a prefix or a suffix to all activity numbers, or specific text or a number to all activity names. However, the added values have to be specified manually even though many of them could have been figured out by a computer had the relationships between the fragnet and the project data been available (Dzeng and Tommelein 2004).

5.2 Knowledge management of Conpla-CBR

Dubitzky (1999) proposed that case-based reasoning process as a knowledge management process. The construction schedule based on the CBR can be managed as a knowledge management. Conpla-CBR can be categorized largely into two items : case accumulation and case utilization. Fig. 5 shows the knowledge management of Conpla-CBR.

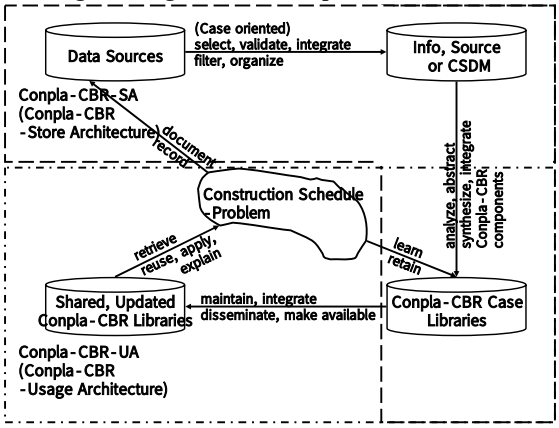

Figure 5. Knowledge management of Conpla-CBR

The part shown in dotted line is the accumulation part of construction schedule case such as Conpla-CBR-SA, info, Source or CSDM and Conpla-CBR Cases Libraries. The construction schedule data or information are selected, validated and integrated from the data source to information, Source or CSDM through the filtering and organizing method. The information, source or the data of CSDM are analyzed and abstracted from the information, source or CSDM to the Conpla-CBR case libraries through synthesizing, integrating and component method in the accumulation part.

On the other hand, the part shown in dashed-dotted line is the utilization part of construction schedule case such as Conpla-CBR Cases Libraries and Shared, Updated Conpla-CBR Case Libraries. The information or data of Conpla-CBR Case Libraries case are maintained and integrated to the Shared, Updated Conpla-CBR Case Libraries through disseminating method and available method.

Data or information from the construction schedule problem (real world problem) are documented or recorded to the Data Sources and learned or retained to the Conpla-CBR Libraries. Therefore the knowledge management of Conpla-CBR is that the case information from the Shared, Updated Conpla-

CBR Case Libraries are retrieved, reused, applied, and explained to solve the construction schedule problems.

5.3 the cycle of Conpla-CBR

The cycle of Conpla-CBR is shown graphically in fig. 6 and (revised from Aamodt and Plaza (1994)).

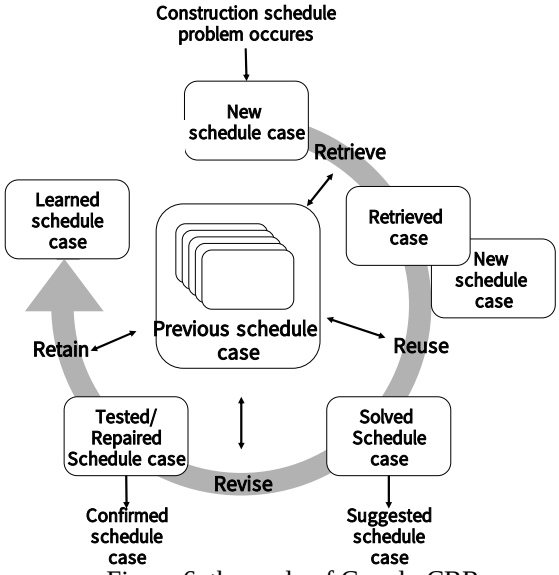

Figure 6. the cycle of Conpla-CBR

The first sub task is to *retrieve* one or more similar schedule cases from the schedule case library where former construction project schedule experiences are stored in the form of previous schedule cases. The main hypothesis behind CBR is quite simply "similar construction schedule problems have similar construction schedule solutions", "you can reuse the schedule solution of a similar schedule problem in order to solve your actual problem". Based on this hypothesis, the second sub task is to *reuse* the similar construction schedule case. But the construction project situations are different case by case. So the third sub task is to *revise* the schedule case just as much as necessary. The last step stores valuable confirmed construction schedule solutions for further reuse. This step is called *retain* and completes the construction schedule experience feedback loop that is a necessary prerequisite for enabling a system to learn form construction project experience (Althoff and Bartsch-Spörl (1996)).

5.4 the process of Conpla-CBR

The process of Conpla-CBR is shown graphically in fig. 8 and (revised from Turban and Aronson (2001)). Boxes represent Conpla-CBR processes, and ovals represent knowledge structure.

The major steps in the Conpla-CBR process are described in the following list.

(1) Assign indexes : features of the new construction schedule event are assigned as indexes characterizing the construction situation or outline.
(2) Retrieve : the indexes are used to retrieve a similar past schedule case from CSDM. The past schedule case contains the prior construction project schedule case.
(3) Modify : the old schedule case is modified to conform to the new construction project situation, resulting in a proposed construction project schedule.
(4) Test : the proposed construction schedule is tried out in construction field. It succeeds either fully or partially.
(5) Assign and store : if the proposed construction schedule succeeds, then assign indexes and store a construction schedule. The successful construction schedule or plan is then incorporated into the CSDM.
(6) Explain, repair, and store : if the construction schedule solution fails, then explain the failure, repair the work plan. The explanation process identifies the source of the construction schedule problem. The predictive features of the problem are incorporated into the indexing rules to anticipate construction schedule problem in the future. The partially succeeded construction plan is repaired to fix the construction schedule problem and the revised schedule is then stored for the using of following construction project.

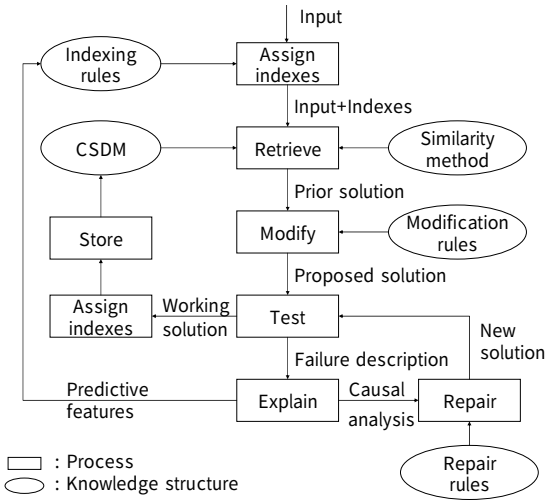

Figure 8. the process of case-based reasoning

To support of this process, the types of knowledge structures, represented by ovals, are described in the following lists.

(1) Indexing rules : indexing rules identify the predictive features in the input that provide appropriate indexes in the CSDM. Determining the significant input features is a persistent problem.
(2) CSDM : CSDM is the episodic memory, which comprises the database of construction schedule case experience.
(3) Similarity metrics : if more than one case is retrieved from episodic memory or CSDM, the similarity metrics can be used to decide which schedule case is more like the current

construction project situation. Modification rules : No old construction schedule case is going to be an exact match for a new construction project situation or outline. The old construction schedule case must be modified to fit. So the knowledge about what kinds of impact factors on construction schedule can be changed and how to change them must be recognized.

(4) Repair rules : Once users identify and forecast an expected failure, user must try to alter the construction schedule or plan to fit the new construction project situation.

Acknowledgments

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ACTION-BASED UNION OF THE TEMPORAL OPPOSITES IN SCHEDULING: NON-DETERMINISTIC APPROACH

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It is the time resource that one deals with in scheduling. The task is how one can achieve the optimal allocation of a given time resource over a set of assigned activities. Most of the existing scheduling methods use a parametric time by which the activities are orderly allocated in accordance with the order of events. The parametric methods however fail in incorporating a dynamic aspect of scheduling that unfolds itself as the project proceeds, and also uncertainty that the starting and ending nodes of an activity fluctuate. This paper reformulates the concept of time to match to a dynamic scheduling through a non-deterministic approach. In particular, time can be regarded as an object in the holographic space, which models the dynamic aspects of time as a "mapped/ represented" and "transformed/ processed" temporal movement.

Keywords: *union of opposites, internal and external order of time, initial and final conditions, dichotomy, temporal symmetry and asymmetry, certainty and uncertainty, entropy*

1. INTRODUCTION

It is the time resource that one deals with directly under any scheduling scheme. The task is how one can achieve the optimal allocation of a given time resource over a set of assigned activities. The temporal order of the assigned activities is usually described in a Network Chart schematically. Then there are various existing methods how to allocate the activities over time, such as Gantt chart, CPM, PERT, GERT, Multi-Activity Chart, and many others[1] [2] [3] [4]. Most of the existing methods use a parametric time, single dimension of time, on which the activities are orderly allocated in accordance with the order of events. They provide, however, one with only a means of static description of time resource distribution at his planning stage, or mere projection of his temporary thoughts in succession. One faces two basic problems in scheduling, namely; (1) (planning stage) the provided data by which time resource is allocated to a particular construction activity is usually far from precise unlike machine operation in manufacturing, where the beginning and ending nodes of a time interval allocated for a particular activity are both fluctuating to a notable extent. Most of the existing scheduling methods [5][6][7] can not incorporate uncertainty of this sort sufficiently enough or not at all. (2) (operating stage) One faces often the need to reallocate the time resource as a construction project proceeds. Although the final goal of the project is clearly defined, no existing scheduling method provides a dynamic adjustment mechanism in reference to the project's goal.

This paper deals with these fundamental problems directly which look different apparently, but they are deeply related, and provides the readers with approach to their solution. For that matter, the authors start with a metaphoric introduction of the guiding concept throughout this paper, "Union of Opposites". The main reason why the existing methods fail in incorporating both fluctuation and dynamic decision mechanisms in their models goes back to the origin of static dichotomy. It will be shown (Section 3) that the concept of time, rooted in static dichotomy, is needed to be reformulated accordingly. The final condition then becomes apparent for human activities vis-à-vis the initial condition (Section 4). Temporal symmetry and asymmetry in scheduling will be discussed (Section 5). Finally, incorporation of uncertainty into the scheduling model will be shown (Section 6).

2. GUIDING CONCEPT, "UNION OF OPPOSITES"

2.1 Act of Mutual Determination in Dichotomy

The flocks of wild geese fly in the Escher's paint (Fig.1) [8], white geese to the right, black ones to the left. These two flocks, though toward the opposite directions, do not only fly next each other but, in fact, *determine* each other in dichotomous fashion. Without the black flock drawing the white, no white flock is defined. Without the white drawing the black, no black flock. The act of mutual drawing is indeed the characteristic of this picture here. Before this act

of drawing, none altogether, no whole nor parts, that is no picture! After this act, the whole picture becomes itself, parts and whole altogether. Escher draws, in this paint, the act of mutual determination in the dichotomy, black and white. This sort of mutual determinant dichotomy the authors call "extended dichotomy", in which *action* is inherently embedded.

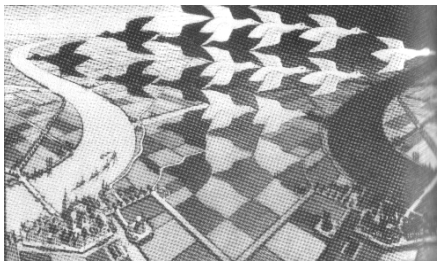

Fig1. Day and Night, M.C. Escher (1938)

2.2 Reflectors

Two mirrors stand still face to face, the one called "white mirror" and the other called "black mirror". The two mirrors reflect each other. The image of the white mirror is at the black mirror, and its image is then reflected back onto itself. The other way around for the black mirror is also true. It can be said, though admittedly metaphor, that when the mirror's image is reflected back onto itself, it becomes itself as *is* a mirror. If a shade screen is set between the mirrors, they are no longer reflecting mirrors. They are not mirrors without continuous movement of reflection of two. The act of continuous reflection maintains the dichotomy, black and white. The two flocks in the Escher's paint are, in this sense, reflectors [9].

2.3 Formalism in Abstraction

The action-based "extended dichotomy" described at (1), (2) can be formalized as follows. Let σ be the underlined action operator, and σ^{-1} be the reverse action operator. In the case of the Escher's paint, σ may be "(the white flock) draws …." σ^{-1} be "(the black flock) draws …." In the case of the mirror reflection, σ may be "(the mirror A) reflects itself on…." σ^{-1} be "(the mirror B) reflects itself on…." In either case the following property of the operators is required;

$$\sigma^2 = \sigma^{-2} = 1 \qquad (1)$$

The operator σ contours the whole circle Ω (logical whole) clockwise, whereas the operator σ^{-1} contours the whole circle Ω counter-clockwise. Then, by combining these two movements, the right-hand of the equation in Fig.2 follows, where both A and not-A are defined explicit, while the movements are hidden behind ($\sigma\sigma^{-1}=1$). It is needed however to keep A and not-A defined explicit that the operator and reverse operator act restlessly behind the back.

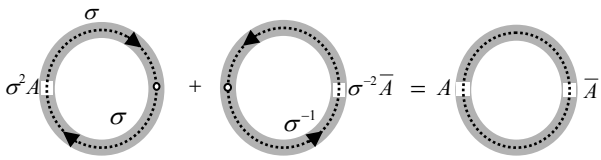

Fig.2 Movement of Action
Holding the Dichotomy Explicit

The continuous convolution of movements, back and forth ceaseless movement between the right-hand and left-hand sides of the equation in Fig.2 to hold the underlined dichotomy explicit, is indeed the notable characteristic of the "extended dichotomy". Under this scheme, it can be said "A is an implicit constituent of not-A. Not-A is an implicit constituent of A.", for both A and not-A equally cover the whole dichotomy space. Or equivalently, "The whole dichotomy space Ω is an implicit constituent of A and of not-A." The usual dichotomy is a degenerated case of the "extended dichotomy", where the operator σ is the set theoretical operation, taking the complement, Ω-A, or Ω-(not-A).

This movement is dictated in the Escher's drawing, for all its compositions, the white and black flocks, and the whole are carefully being adjusted under the movement. The white and black flocks in the picture are therefore restlessly flapping around the sky of logics, back and forth ceaseless movement

3. IMPLICIT AND EXPLICIT ORDER OF TIME

It is the time resource that scheduling deals with. One's parametric conception of time causes action of any kind dropped off from a scheduling model. However useful the parametric conception may be as scaling tool to determine the time interval during which an activity proceeds. It should be realized however an activity comes first and determines the time interval, but not the other way around. The fact that there exists the order of action behind the parametric time must be incorporated into a scheduling model. It is the implicit internal time, another temporal order, more fundamental one, which casts its shadow over the parametric time. It is this temporal order within which the current activity is adjusting to its immediate as well as accumulated past and anticipating the coming future.

There are two distinct temporal orders, implicit and explicit. The implicit order of time is the order of action in which the past, present, and future of an activity are convoluting as potentials, while the explicit order of time is the parametric time of events measured by mechanical clock.

3.1 Schematic Formulation of Internal and External Time

Two streams of activities in the form of potentials flow into the current activity, one from the past and the other from the future [1]. They convolute at present,

bounce around their way of settlement, come to a conclusion as to their optimal mixture, and in the end transform the integrated potentials into an event at now which belongs to the explicit order of time. The implicit and explicit temporal orders categorically differ in such a way that one deals with *potentials* in the implicit order of time, but deals with *events* in the explicit order of time. However they are distinctively different, they are dynamically integrated within the dynamics of the current action, two sides of the same coin.

[1] *The potentials from the past and those from the future are distinctive, for the activities in the past have already happened and became events once, while the activities in the future are in the mode of pure potentials. Though the past activities became unchangeable events as they were, they can be viewed from the standpoint of the current activity as potentials, for the ones who conduct the current activity must give them a particular interpretation among many possible interpretations to find an optimal fix with reference to its immediate, intermediate, and final goals, all to be happened in the future.*

The authors now formulate the combinatory temporal order, Internal Time x External Time at Fig. 3.1. Each internal time is non-locally distributed over the pre-assigned temporal whole, Ω with density function $f_j(t)$ *such that* $\sum_j f_j(t) = 1, \forall t \in \Omega$ The dynamic movement between the internal time and external time described above can be formulated as Temporal Engine, and put into the schematic form diagrammed at Fig. 3.2.

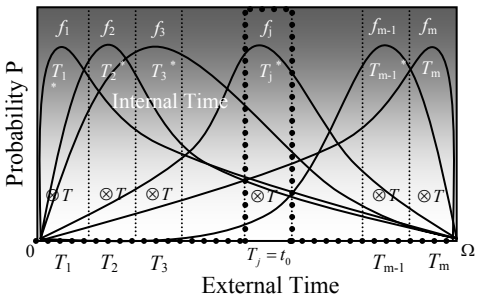

Fig.3.1 Internal Time and External Time

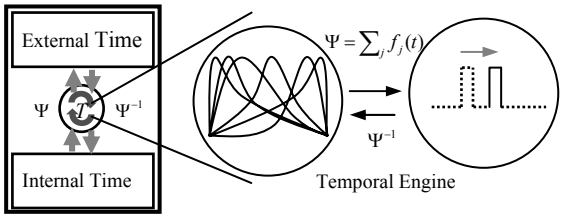

Fig.3.2 Temporal Engine: Two-way Transformation Between Non-Local Internal Time and Local Time

The event produced by the current activity is indeed dichotomous whether it happens (1) or it does not happen (0). This eventual dichotomy however becomes explicit only through superposition of all the internal potentials and its transformation. There is yet another fundamental dichotomy between the internal and external time, two-way action-based dichotomy actuated by the Temporal Engine. It is more fundamental for it makes the former possible.

3.2 Mathematical Formulation: Holographic Modeling

In this section, a more rigorous formulation will be outlined and reveal it has a holographic characteristics. Let the set of the probability density functions shown at Fig.3.1 be denoted by $\{f_\theta(x)\}_{\theta\in\Omega}$, each of whose elements is a non-locally distributed internal time centered at each time $\theta \in \Omega$. One can change the *x*-coordinate to $[-\pi, \pi]$ without loss of generality. The set of densities ($\int_{-\pi}^{\pi} f_\theta(\tau)d\tau = 1, \forall \theta \in \Omega$) is assumed to satisfy either of the following conditions.

(1) Stronger condition (symmetry)
$$\vartheta_1 = \{f_\theta : f_\theta(\tau) = f_\tau(\theta)\}$$
(2) Weaker condition (integral symmetry)
$$\vartheta_2 = \{f_\theta : \int_{-\pi}^{\pi} f_\theta(\tau)d\tau = \int_{-\pi}^{\pi} f_\tau(\theta)d\tau\}$$

Even the stronger condition holds for most of applications because of the homogeneity of time, that is no time is usually special to any other time.

One can decompose each density function by Fourier Harmonic Decomposition, that is;

$$\bar{f}_\theta^{c(n)} = b_\theta(n)\cdot\cos n\tau$$
$$\bar{f}_\theta^{s(n)} = a_\theta(n)\cdot\sin n\tau \qquad (2)$$
$$where \quad a_\theta(n) = \frac{1}{\pi}\int_{-\pi}^{\pi} f_\theta(t)\sin ntdt$$
$$and \quad b_\theta(n) = \frac{1}{\pi}\int_{-\pi}^{\pi} f_\theta(t)\cos ntdt$$

Those harmonic components can be rearranged on the surface of a unit sphere, for it gives the circumference on the unit sphere to multiply by 2π the sine and cosine functions in each harmonic component (Fig.3.3). Thus one obtains its geometric interpretation.

It is further possible to reduce all the sine and cosine harmonic components to the sine harmonics only, for a cosine harmonic can be viewed as sine harmonic when the

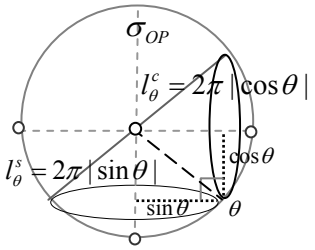

Fig.3.3 Geometric Interpretation of Fourier Harmonic Decomposition

unit sphere is rotated to counter-clockwise by $\pi/2$ (angular duality of sine and cosine circumferences). After such rearrangement of Fourier coefficients and sine-reduction, one can assign each slice of the unit sphere a unique value of coefficient (Fig.3.4) named as "holographic coefficient" (by the authors). Those coefficients are uniquely determined by the underlined set of probability density functions which represent collectively the structure of the internal time under consideration.

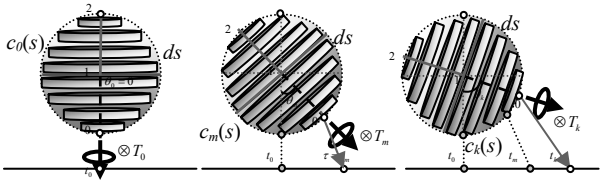

Fig.3.4 Unit Sphere Representation of the Internal Time with Holographic Coefficients

The unit sphere therefore encodes all the information as to the internal time configuration on its surface with the values of coefficients assigned to each slice that will vary in general by its angular inclination. When one takes the integral of the coefficients over the sphere surface from a particular angle (say θ_m), one gets the corresponding external time t_m. One can now defines an operator called "holographic operator" (by the authors) which acts on the sphere surface, and whose action produces an external time each time it acts on the surface.

$$\sigma_{OP} = 1 + \frac{1}{2\pi}\int_0^{4\pi} < operand > ds$$

$$\otimes T_\tau = \{c_\tau(s) : 0 \le s \le 4\pi\}$$

= set of coefficients as operand at time

$$\sigma_{OP} \otimes T_\tau = 1 + \frac{1}{2\pi}\int_0^{4\pi} c_\tau(s) ds = 1 \qquad (3)$$

The holographic operator acts on the same sphere all the time, changing its angular direction in succession, casting the shadow of the sphere, producing the eventful world, and thus bridging the potentials with reality, that is that the action-based "extended dichotomy" is.

4. INITIAL CONDITION AND FINAL CONDITION

In physics or engineering alike, physical events evolve over time by certain differential equations autonomously once given initial conditions. The equations and its initial conditions determine the whole sequence of the following events. The Newtonian physics and Einstein's relativistic physics both belong to this deterministic world. The Schrödinger's wave equation in the Quantum physics is not an exception, though the square of the wave amplitude gives probability with which an underlined particle may be there. Moreover, most of the physical laws cannot distinguish two directions of time [10], from past to future, and future to past. They are temporally symmetric from the standpoint of the underlying physical equations. The initial conditions can be set in the future in stead of the past to get exactly the same sequence of events, but in the reversed order.

But in reality or at least reality of large-bodies nobody says time runs backward. It is the thermodynamics that provides us with the arrow of time. The entropy, the measure of disorder, always increases according to the law. Suppose there is a cluster of gas molecules at one corner of an enclosed box. These molecules tend to move to random directions due to their bouncing around collisions so that they diffuse eventually to the whole space in the box. However the probability that the once diffused molecules gather back to a corner is negligibly small though not zero, but very rare statistically, for the number of ways of the diffused state far exceeds that of consolidate states. It is the thermodynamic law that preserves the time symmetry of the basic physical equations, while reveals the phenomenological arrow of time. The physics of non-equilibrium processes describes the profound effects of unidirectional time which lead to concepts such as self-organization and dissipative structures [11][12].

Here raises a basic question, however, whether the human activities are bounded by the second law of thermodynamics. The physical law is so basic that the answer should be affirmative. That is why some people's desktop becomes messy. Then the next question follows immediately whether the consolidate states in human activities are so rare compared to their disorder states as the law of thermodynamics may suggest. How about in the case of scheduling? How about in the case of baseball spectators? After an inter-company baseball match between Company A and Company B is over, a crowd of spectators once seated orderly leave the stadium to different directions to home. The ordered state is broken there, that is increase of entropy. Next morning people from Company A go work at Company A and people from Company B go work at Company B. They are in very orderly state to work for their company's profit-making. If you replace the molecules with humans in the box, perhaps in a room this case, the consolidate states are likely, or at least as likely as the diffused states.

What makes them different is due to that the final condition (goal) which acts on their activities throughout time become notable in the case of human activities. For it is the human activities that are arranged in construction scheduling, one must consider two conditions lie at the two opposite ends of the construction period, the initial condition and final condition. They are defined as follows;

Initial Condition − the ordered state of the initial plan or design on the onset

Final Condition − the ordered state of the physical achievement at the end.

The two conditions are both in ordered states, but distinctively different ones. The initial condition lies at the onset of the project when no events have yet happened. It is therefore something to do with the planning or design of the scheduling. The final condition lies at the end of the project. It is therefore something to with the physical achievement (say a building). The initial condition acts on the internal time throughout time for it deals with potentials, while the final condition acts on the external time throughout time for it deals with events. As the project proceeds, the initial condition acts less and less, while the final condition acts more and more and reaches to the completion of the project. When reversing the time backward, the initial condition acts more and more, while the final condition acts less and less. Such two ways process is depicted at Fig.4.1 (a) (the white flock represents the initial condition on the internal time, while the black flock does the final condition on the external time). At any section of time one finds both orders act.

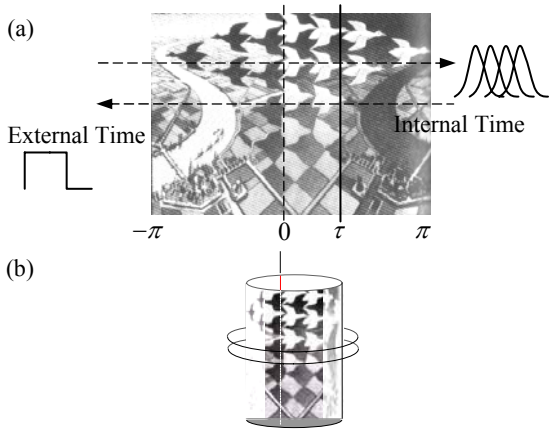

Fig.4.1 Initial Condition and Final Condition

After the project is over, it spins off new different but similar projects and lets them commence at the point that it ends (Fig.4.1 (b)). In this way the following independent projects are the precedent project's offspring that have both continuity and discontinuity from the precedent ones. The phase transition occurs at the point that the parent project ends from the physical external order to the internal order in which "genetic" crossovers [13] with other projects occur.

5. TEMPORAL SYMMETRY AND ASYMMETRY

The holographic operator acts on the operand distributed over the sphere surface from a different angle at each time and sums it up to produce the external event (Fig.5.1 (a)). All the information on the whole surface of the sphere is encoded at each slice on the sphere due to the underlying holographic characteristics. Therefore each coefficient can be decomposed into its past and future parts ($c_\tau(s) = c_\tau^{past}(s) + c_\tau^{future}(s)$). One can therefore decompose the holographic operator (Section 3.2) into the past and future sub-operators as follows;

$$\frac{1}{2\pi}\int_0^{4\pi} c_\tau(s)ds = \frac{1}{2\pi}\int_0^{4\pi} c_\tau^{past}(s)ds + \frac{1}{2\pi}\int_0^{4\pi} c_\tau^{future}(s)ds \quad (4)$$
$$\text{that is } \sigma_{op} = \sigma_{op}^{past} + \sigma_{op}^{future}$$

The information of the past is distributed over the whole surface of the sphere. So is the information of future. It is a perfect symmetry as a sphere is. When the holographic operator acts on the sphere at each time and sums it up to produce the external event, the symmetry is broken (Fig.5.1.(b)). Each time when it happens, the sphere remains symmetric, but attains an induced asymmetry (redefined past, present, and future).

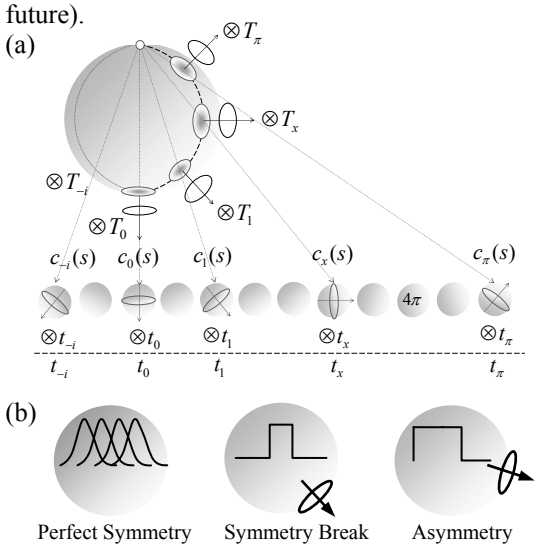

Fig.5.1 Temporal Progression and Symmetry Break

6. CERTAINTY AND UNCERTAINTY

In Section 4, it seemed suggested the second law of the thermodynamics may be broken in the case of human activities. One cannot jump into such a conclusion however. The issue is more subtle than it seemed. Although it is true that once the final condition acts on the component activities to a notable degree (such is the case for scheduling), the ordered states become as likely as the disordered states or more likely, the disintegration pressure due to the thermodynamics law acts on the activities all the while the project proceeds. There are indeed so many sources of disintegration in a project which may halt the project at worst (all sorts of troubles in logistics, crane operation, weather, structures, water leakage, accidents, financing, and so on as you can imagine).

This disintegration pressure comes from the depth of the physical world, back to the turbulent movements of molecules. It suggests all sorts of the dichotomies mentioned in the earlier sections do not stand in the idealists' binomial opposition, but are real opposites.

That is the reason why any planned activity is realized hardly as precise as planned, its beginning and ending points fluctuate to a notable degree, and needs to be continually adjusted under the persisting circumstance that the initial and final conditions actively colliding.

The thermodynamics law is not negligible at all for scheduling. However it is also true it is hard to hold the assertion that the diffused states are more likely in human activities. By the same token, for scheduling. The internal time is non-locally distributed over the whole time with some fluctuation. The thermodynamic fluctuations are in fact implicitly embedded there [3]. The node between the successive activities becomes vague and is stretched over some interval in this setting (Fig.6.1). Contrarily the event becomes realized with certainty, once it happens.

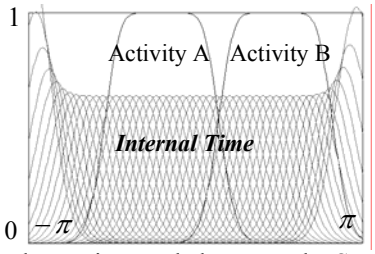

Fig.6.1 Fluctuating Node between the Successive Activities

7. SUMMARY

It was shown that the order of time should be reformulated to model the evolutional aspect of scheduling as the project develops towards its completion. Its dynamics requires dealing with the temporal potentials set for scheduling the whole set of which unfolds events in successions as time passes and enfolds them back to itself to continually refer to both the initial conditions at the onset of the project and the final conditions imposed at its completion. The mathematical modeling of the underlined dynamics by Fourier harmonic decomposition reveals its holographic characteristic *that is* the back and forth movement between encoding and decoding of the information of the whole.

It was also shown that, deeply related to the dynamics, the fluctuation of the activity's nodes can be formulated as the temporal non-locality of the internal time and that the second law of thermodynamics can be reinterpreted in such a way to fit the human activities *per se*.

Whitehead's process philosophy opened up a new line of thoughts that the process of becoming comes before existence [14]. This paper has showed it is indeed the case for scheduling as well.

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SCHEDULING MODEL CONSIDERING CONSTRUCTION INTERFACES FOR BUILDING PROJECTS

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Abstract: Practitioners often manage construction interfaces and scheduling separately. However, poor management of construction interfaces frequently causes delays in project duration. This work develops an innovative scheduling model that incorporates management of construction interfaces for building projects. The proposed model comprises five steps, including generating an integrated schedule, establishing interface work groups, identifying front- and post-holding activities for each work group, mapping interface events, and transforming to a construction interface based network schedule. The developed schedule network has fewer activities, links, and paths than the conventional schedule network, increasing readability and schedule control.

Keywords: Interface management, construction interface, network scheduling, and schedule control.

1. INTRODUCTION

Building construction project execution frequently involves several contractors, such as civil/ architect/structure (CSA), mechanical/electrical (M/E), etc. These contractors must perform certain construction activities to erect various physical objects (such as reinforcing steel, forms, pipes, and facility equipment) in particular locations or spaces. However, proper sequence arrangement of the activities and well-combined shop drawings of these objects are required in advance to avoid interface problems that may cause work disturbances during the erection of these objects. A work disturbance caused by an interface problem can be a stoppage of one activity to wait for another, degraded functions, a change request, or even a costly reworking [1]. An accumulation of disturbances for several activities may delay the entire project and increase the project cost. These consequential delays or extra costs are exaggerated when the project is complicated or involves numerous contractors.

Regarding interface management, most recent research has focused on construction space management, including site layout planning techniques for reducing space conflicts and scheduling techniques considering space constraints. For example, the MovePlan system [2] treats "space" as a resource to be attached to each activity in a construction schedule. The system enables the modeling of site space needs during project scheduling and space conflict on the site is eliminated by adjusting the schedule. Thabet and Beliveau [3] developed a scheduling model by quantifying workspace demand and availability parameters for multistory buildings. Riley and Sanvido [4] established a space planning method to identify the specific spaces needed for activities, define locations for these spaces on multistory building construction, develop a work sequence that defines the order in which spaces are occupied, and identify potential spatial conflicts. Finally, with particular reference to building facade interfaces, Pavitt and Gibb [5] discussed interface management in three categories ─ physical, contractual, and organizational, and then created an interactive software tool to provide a strategy for optimizing the technical and management aspects of cladding interfaces.

Although the management of construction interfaces has been recognized to significantly dominate construction duration performance, interface management and schedule control still are poorly linked in practice. Without definite scheduling information to support their intensive efforts, the field engineers do not know the deadline for resolving particular interface problems, and nor do they know which interface problems are more urgent than others for preventing delays or unnecessary costs. This study presents an innovative scheduling model that considers the construction interfaces for supporting both schedule control and interface management [6].

2. DEFINITION OF CONSTRUCTION INTERFACE

This study defines a construction interface as either a physical connection between two or more construction objects, a working contact between two

or more object-erecting activities, or a constructability problem caused by poor design details or conflicting design information. Possible interface problems related to each type of construction interface are listed below:

- Physical connection. — The embedded connection is an example. Additionally, for example, pull boxes are attached to the finish of an interior wall (i.e., an "attached" interface); and M/E pipes cross with one another in a limited duct space (i.e., a "space interfering" interface) [1].
- Working contact. — Typical examples include the conflict in activity sequence, interruption of activity working path (e.g., large scale M/E equipment must be moved into a room before construction of that room is completed by the C/S/A), and competition for limited temporary working space (e.g., C/S/A's finish activity and M/E's equipment installation activity are performed in a room with limited space).
- Constructability problem. — For example, permanent room space is insufficient for accommodating multiple pieces of facility equipment; and difficulty arises in assembling construction components.

3. PROPOSED MODEL

Developing the proposed construction interface (CI) based scheduling model is an attempt to treat network activities identified as interfering with others as a single interface work group. Several work groups are established in the aforementioned integrated schedule. Figure 1 illustrates the implementation of this idea. The upper of Figure 1 displays a conventionally integrated schedule network with four individual schedules (prepared by four different contractors), and the bottom portion displays an established CI-based schedule network. This proposed model is detailed as follows: (1) major terminologies are defined, (2) typical interface problems in building construction are identified, and (3) the modeling steps are presented.

3.1 Interface work group, interface event, and holding activities

As shown in Figure 1, the CI-based scheduling model proposes a method of using interface work group (WG), interface event (IE), and holding activities to help represent construction interfaces in the schedule. An interface WG comprises a set of activities that are executed on the same building component (for example, a wall, slab, ceiling or girder) and/or are executed using the same working space (for example, a ceiling void or a room) within a short period. An interface WG can be viewed as a work package for managing the interface problems of a particular construction component or working space.

The activities in a WG are divided into three parts: a front-holding (FH) activity, one or more interface events (IEs) established by the in-between activities of the WG, and a post-holding (PH) activity. The FH and PH activities represent the start and end points of the WG, respectively. That is, an interface problem for a specific WG does not emerge until the FH activity starts, and will not be entirely resolved until the completion of the PH activity. When a WG comprises multiple IEs, additional middle FH and PH activities should be identified from the in-between activities.

The in-between activities of an IE are concurrently or sequentially executed and have several interfaces among them. Since these interfaces are interrelated, it is preferable to care for these interfaces as a whole, that is, a single event. Thus, from the management perspective, an IE can be treated as a small work package dealing with a particular set of interfaces. The interfaces between different IEs can be assumed to be uncorrelated. That is, IEs can be resolved individually.

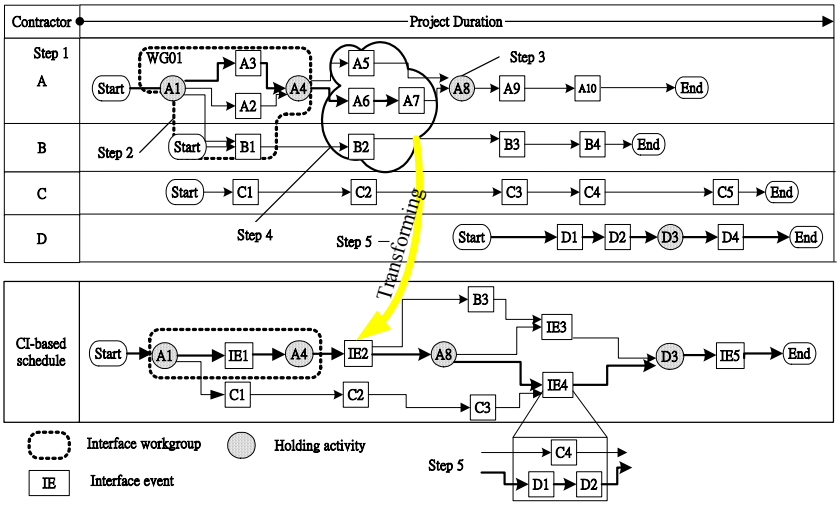

Figure 1. Idea of the CI-based scheduling model

3.2 Typical interface problems in building construction

Building project construction may be broadly divided into several stages, namely: site preparation, foundation construction, underground and upper structure, finish, and equipment installation. During the early stages, construction interface problems generally are minimal because the involved major activities (e.g., piling, slurry wall construction, and excavation) usually are performed by a single C/S/A contractor (who easily can resolve any interface problems among their subcontractors or trades) and the design details are less complex.

Structure related. In constructing certain structural components (such as columns, girders, beams, and slabs), interfaces frequently occur among C/S/A, M/E, and other contractors. For example, in pouring concrete for a floor slab, after completing a surveying activity (i.e., a FH activity), activities of placing bottom reinforcing steel, forming, placing cast-in sleeved pipes, plumbing, and placing top reinforcing steel (or top mesh) are performed sequentially or concurrently. The concrete can be poured only after these activities are completed. A delay in concrete pouring often results if the work of the M/E in placing cast-in sleeves and plumbing is not finished in time. Also, if the composition of the required shop drawings is poor, then a high density of placed cast-in sleeved pipes and electrical tubes is likely to be impossible to fully embed inside in the slab within a limited space (e.g., a slab with a thickness of only seven inches).

Finish related. The finishing for ceilings, walls, and slabs also is an area of common interface problems. For example, ceiling construction may include surveying, framing, stud setting, placement of electrical tubes, mechanical pipes (including fire protection plumbing, air conditioning ducts placing, and others) and first panel, lighting fixture installation, second panel placing, and painting. Usually, the work begins with surveying, moves on to first panel placement, and ends with painting. The completion of ceiling work thus can be divided into two parts here, namely the ceiling-1 and ceiling-2 interface events. Construction interface problems for the first IE (i.e., ceiling-1) mainly result from either the limited space (for installing high density of tubes, pipes, and ducts) or the complex activity sequences. A suitable composite shop drawing thus should be generated in advance to ensure that all construction materials can be installed in the ceiling. Additionally, contractors must negotiate an appropriate sequence (i.e., when to transfer the working space to another contractor, once a contractor has finished a particular part of his work). Further reworking after the completion of the first panel placing is not welcomed. After the first IE activities are completed, lighting fixtures, air conditioning system diffusers, and fire alarm sensors can be installed, followed by the second panels. Again, reworking after completing the ceiling painting is discouraged.

Equipment installation related. Interface problems may occur when installing equipment to a specific location, such as to an air conditioning (AC), electrical power (EP), or control center (CC) rooms. The issues related to this type of interface problem include the conflict between equipment move-in time or move-in path, limited space for accommodating equipment, and the constructability of physical connections between equipment and structural components.

First, equipment can be installed in a room either before or after room completion depending on equipment size. For example, large sized equipment generally must be placed in a room before the surrounding structure (namely, walls and ceiling) of the room is completed. Otherwise the door of the enclosed room would simply be too small for the equipment to pass through. Although disassembling-and-reassembling the equipment offers an alternative solution, this approach can compromise future equipment performance quality. Consequently, another common solution is for the C/S/A contractor to leave a temporary "hole" in the wall or ceiling during concrete reinforcement. After the equipment is moved in by the M/E contractor, the C/S/A contractor then closes the hole. In addition to this interrelated sequence (namely, C/S/A→M/E→ C/S/A), the equipment move-in time (namely, when the equipment is moved into the room), move-in path, and move-in conditions for transferring the room between contractors have to be set in advance.

Second, some equipment-related interface problems arise because of specific room spaces being too small to accommodate all pieces of equipment. This problem can be resolved either by procuring different sized equipment or changing the room size. Third, certain equipment-related problems commonly exist in the physical connections between the structure and facility equipment.

3.3Modeling steps

The proposed CI-based scheduling model includes the following five steps (see Figure 1).

Step 1: Generating an integrated schedule. The construction of a building project often involves multiple subprojects. Since all subprojects must be completed for the entire building project to be useful, the management of the various subprojects preferably should be integrated. The schedules of these subprojects thus should be integrated into a single schedule. Such an integrated schedule can be established by connecting the activities of the individual schedules according to the logical relationships between activities. For example, M/E

plumbing activity (say, activity A) cannot be started until C/S/A surveying activity (say, activity B) is finished, and must be completed before C/S/A concrete pouring activity (say, activity C) can be started. The links B→A and A→C thus can be established.

Step 2: Establishing interface work groups. This step involves establishing the interface WGs in the integrated schedule. For example, Figure 1 shows that activities A1, A2, A3, and A4 of contractor A, and activity B1 of contractor B are grouped to comprise WG01. Based on the previously analyzed typical interface problems in building construction, five typical interface WGs are identified (Table 1): the reinforced concrete (WG01) is structure related; the ceiling (WG02), wall (WG03), and raised slab (WG04) are finish related; and the equipment installation (WG05) is equipment installation related.

Table 1. Typical interface WGs, IEs, and holding activities in building construction

Construction stage	Work group	Building component	Type of IE	FH activity	Typical in-between activities	PH activity
Structure	WG01: Reinforced concrete	Column, girder, beam, slab	Column, girder, beam, slab	Surveying	Cast-in sleeved pipes placing, forming, reinforcing, plumbing	Concrete pouring
Finish	WG02: Ceiling	Ceiling	Ceiling-1	Surveying	Framing, stud setting, AC duct placing, place M/E tubes and pipes, first panel setting, lighting fixture installation	First panel placing
	WG02: Ceiling	Ceiling	Ceiling-2	First panel placing	lighting fixture installation, second panel placing	Painting
	WG03: Wall	Interior wall	Interior wall	Stud setting	First side panel placing, AC controller installing, electric pull box placing	Second side panel placing
	WG04: Raised slab	Raised floor	Raised slab	Surveying	Slab framing, AC duct placing, cable tray installing	Cover plate installing
Equipment Installation	WG05: Equipment installation	AC room, EP room, CC room	AC room, EP room, CC room	Ceiling painting, or second side panel placing of interior wall, or raised floor cover plate installing	Equipment base foundation, equipment components installing	Installing last piece of equipment

IE: interface event, FP: fire protection, AC: air conditioning, EP: electrical power, CC: control center.

Step 3: Identifying holding activities for each work group. Table 1 displays the FH and PH activities (as well as the IE and typical in-between activities) for each of the five defined WGs. For example, the surveying and concrete pouring activities are the FH and PH activities, respectively, for the reinforced concrete WG. Additionally, the PH activity of a WG can be the FH activity of anther WG.Notably, if a WG has more than one IE (e.g., the ceiling WG), additional FH and PH activities must be identified for confining the IEs. Should this be the case, the PH activity of an IE may be the FH activity of anther IE. For example, in Table 1, the activity of first panel placement plays the roles of the PH and FH activities for ceiling-1 and ceiling-2 IEs, respectively.

Step 4: Mapping the interface events. Once both holding activities for an interface WG are set, the rest of the in-between activities are tied together (called "mapping" herein) to form one or more IEs. Table 1 also lists the six typical IEs of the five identified WGs. Among these six IEs, two (i.e., ceiling-1 and ceiling-2) are related to the ceiling WG. As implied earlier, the ceiling WG is broken into two IEs because each IE can be managed independently without interfering with the other.

Step 5: Transforming to a CI-based network schedule. After determining the holding activities and IE(s) for each WG, the originally integrated schedule easily can be transformed to a CI-based schedule through the following sub-steps:(1) to represent each mapped IE as a single node. (2) To connect each IE to its predecessors (including FH activity) and successors (including PH activity). (3) to evaluate the duration of each IE. IE duration is determined by the longest path in the IE' subnet by applying the CPM forward and backward calculations to this CI-based network .

4. EXAMPLE DEMONSTRATION

Suppose a building construction project is divided into four subprojects that are performed by contractors A, B, C, and D, respectively. A total of 24 activities are associated with these schedules, that is, ten, four, five, and five activities for contractors A, B, C, and D, respectively

4.1Evaluation results

A CI-based schedule for this example project can be generated based on the following modeling steps.

Step 1: Generating an integrated schedule. After examining the interrelationships between these schedules, suppose an integrated time-scaled project schedule is established. Table 2 lists the network data (such as duration, logical sequence, ES, LS, EF, and LF) for each project activity. Based on the Critical Path Method (CPM) calculations, the project duration is 97 days, and the critical path is A1 → A2 → A4 → A6 → A7 → A8 → A9 → A10 → D1 → D2 → D3 → D4 → D5 (as indicated by the dark line in Figure2)

Step 2: Establishing interface WGs. Suppose four interface WGs of activities are established in the integrated schedule (see Figure 2). Activities A1,

A2, A3, A4, and B1 are grouped in WG01; A8, A9, A10, B4, C4, D1, D2, and D3 are grouped in WG02; A4, A5, A6, A7, A8, B2, and B3 are grouped in WG03; and D3, D4, D5, and C5 in WG04.

Step 3: Identifying holding activities for each WG. As summarized in Table 3, activities A1, A4, A8, and D3 are identified as the FH activities for WG01, WG03, WG02, and WG04, respectively. Moreover, A4, A8, D3, and D5 are the PH activities for WG01, WG03, WG02, and WG04, respectively. In this example project, activities A4, A8, and D3 play the roles of both the FH and PH activities. Notably, in WG02 (including two IEs), A10 is the PH activity for IE3 and the FH activity for IE4.

Step 4: Mapping the IEs. In this example project, each WG consists of one or two IEs. That is, each of the WG01, WG03, and WG04 has an IE, namely, IE1, IE2, and IE5, respectively. Additionally, WG02 has two IEs, namely, IE3 and IE4. Table 3 shows the in-between activities for each IE. For example, IE1 for the WG01 has three concurrent activities, that is, A2, A3 and B1.

Step 5: Transforming to a CI-based network schedule. A CI-based schedule network can be established after representing each IE as a single node and connecting each IE to its predecessors and successors, as illustrated in Figure 3. The activities along the critical path (showed by the dark line in Figure 3) include A1, followed by IE1, A4, IE2, A8, IE3, A10, IE4, D3, IE5, and D5. Notably, each IE is on the critical path. Taking WG01 as an illustrative example, A1 and A4 are the FH and PH activities for IE1 (representing three concurrent activities A2, A3, and B1), respectively. In the original integrated network, A1 is linked to A2, A3, and B1, respectively. Following transforming, only one link exists between A1 and IE1, and other two links are not visible in the main network (that is, they are hidden inside the subnet of IE1). Table 4 displays the data on duration, predecessors, successors, ES, LS, EF, and LF for each activity and IE for the CI-based schedule. Notably, the duration of each IE is determined by the longest subnet path. For example, the longest path for IE4 (which comprises C4, D1, and D2) is D1→D2. Therefore, the duration of IE4 is 27 days, which is the sum of the 15 days of D1 and the 12 days of D2. Also, the duration of IE2 is 17 days (=7+10) which is sum of the durations of its two critical activities (that is, A6 and A7).

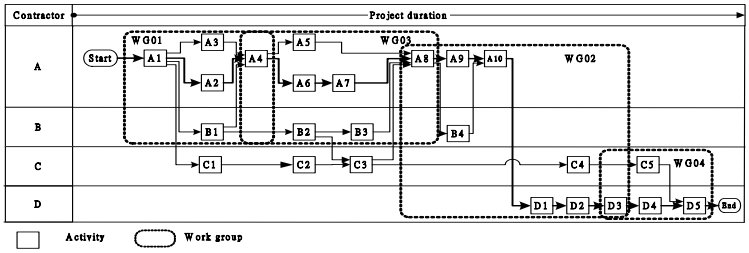

Figure 2. Originally integrated schedule network for the example project

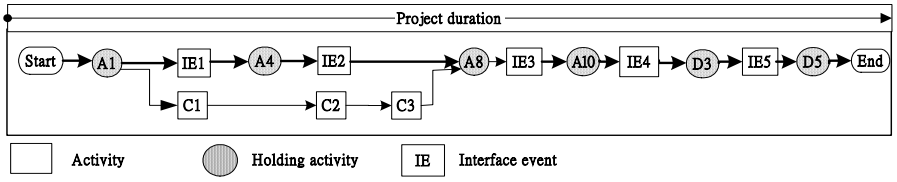

Figure 3. Generated CI-based schedule network for the example project

4.2 *Comparion of CI-based and CPM-based schedules*

The generated CI-based schedule is compared with the original CPM-based schedule in several aspects to indicate the significance of the proposed model. The comparisons are summarized in Table 5 and illustrated as follows.

- Activities. Figure 3 demonstrates that the original 24 activities are reduced to just 14, including five IEs and nine other activities. Among these nine activities, six activities (i.e., A1, A4, A8, A10, D3, and D5) are characterized as either FH or PH activities, and the others (i.e., C1, C2, and C3) are not assigned any special significance in the area of interface management. Also, the number of critical activities is reduced from 13 to 11.
- Links and paths. The number of links is decreased from 31 to 14. Especially, the original 20 network paths are reduced to just two paths existing in the CI-based schedule.
- Project duration. Since the proposed model uses the same basic CPM network calculations, the project durations are the same for both schedules, each lasting 97 days.

5. CONCLUSIONS

This work presents a new scheduling model that integrates both schedule and construction interface management for building construction. The modeling method (that is, establishing work groups, identifying holding activities, mapping interface events, and transforming the schedule) increase schedule readability and hence schedule control effectiveness. Such a readable schedule also provides timing information for resolving interface problems.

Table 2. Network data of the integrated CPM-based schedule for the example project

Act	Dur.	Predecessor	Successor	ES	LS	EF	LF
A1	2	-	A2, A3, B1, C1	0	0	2	2
A2	6	A1	A4	2	2	8	8
A3	5	A1	A4	2	3	7	8
A4	3	A2, A3, B1	A5, A6	8	8	11	11
A5	15	A4	A8	11	13	26	28
A6	7	A4	A7	11	11	18	18
A7	10	A6	A8	18	18	28	28
A8	4	A5, A7, B3, C3	A9, B4	28	28	32	32
A9	5	A8	A10	32	32	37	37
A10	6	A9, B4	D1	37	37	43	43
B1	4	A1	B2	2	11	6	15
B2	7	B1	B3	6	15	13	22
B3	6	B2	A8	13	22	19	28
B4	4	A8	A10	32	33	36	37
C1	3	A1	C2	2	14	5	17
C2	6	C1	C3	5	17	11	23
C3	5	C2	A8, C4	11	23	16	28
C4	2	C3	C5	16	88	18	90
C5	5	C4, D3	D5	80	90	85	95
D1	15	A10	D2	43	43	58	58
D2	12	D1	D3	58	58	70	70
D3	10	D2	D4, C5	70	70	80	80
D4	15	D3	D5	80	80	95	95
D5	2	D4, C5	-	95	95	97	97

ES: early start, LS: late start, EF: early finish, LF: late finish.

Table 3. WGs, IEs, for the example project

Work group	FHa	PH	IE	In-between activities of IE
WG01	A1	A4	IE1	A2, A3, B1
WG03	A4	A8	IE2	A5, A6, A7, B2, B3
WG02	A8	A10	IE3	A9, B4
WG02	A10	D3	IE4	C4, D1, D2
WG04	D3	D5	IE5	C5, D4

FH: front holding activity, PH: post holding, activity

Table 4. Data of CI-based schedule

Activity	Duration	Predecessor	Successor	ES	LS	EF	LF
A1	2	---	IE1, C1	0	0	2	2
IE1	6	A1	A4	2	2	8	8
A4	3	IE1	IE2	8	8	11	11
IE2	17	A4	A8	11	11	28	28
A8	4	IE2, C3	IE3	28	28	32	32
IE3	5	A8	A10	32	32	37	37
A10	6	IE3	IE4	37	37	43	43
IE4	27	A10	D3	43	43	70	70
D3	10	IE4	IE5	70	70	80	80
IE5	15	D3	D5	80	80	95	95
C1	3	A1	C2	2	14	5	17
C2	6	C1	C3	5	17	11	23
C3	5	IE2, C2	A8	11	23	16	28
D5	2	IE5	---	95	95	97	97

Table 5. Comparison of CI and CPM-based schedules

Network	No. of activities	No. of critical activities	No. of links	No. of paths	Project duration
CPM-based	24	13	31	20	97 days
CI-based	14	11	14	2	97 days

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CONSTRUCTION MANAGEMENT PROCESS RNGINEERING - ORGANIZATIONAL HUMAN RESOURCE PLANNING FOR MULTIPLE PROJECTS

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Abstract: Applying the business process engineering and organization planning philosophy, this study focuses on the human resource planning for the construction management process reengineering to develop the team-based human resource planning (THRP) method for humanpower allocation, which assists construction companies for scheming, and assaying humanpower allocation alternatives as the construction management process reengineering was performed. The THRP method aims at two purposes; the first is to determine what the maximum project loading of original humanpower could be carried. Also evaluate the sufficient humanpower to meet the optimal project loading in the future.

Keywords: human resource planning, business process reengineering (BPR), computer simulation

1 INTRODUCTION

The phrase ‘‘business process reengineering’’ (BPR) first appeared in 1990, raised by Michael Hammer in his paper published in the Harvard Business Review called ‘‘Reengineering work: Don’t automate, obliterate’’ [1]. The fundamental definition of BPR as defined by Hammer is that starting from the very basic issues by reformation of the reengineering process will dramatically improve an organization in terms of its cost, quality, service, and speed. Moreover, Davenport also addressed that the process redesign, use of information technology, and the reorganization are the three critical objectives of BPR [2]. Therefore, a success of BPR depends not only on process innovation, but also on organizational changes.

Due to smash of organizational functions, new processes are easily suspended by departmental barriers within the function-based organization. Conversely, process execution will be smoother in a team-based organization [2]. A work team is a cross-functional unit which consists of workers from the related departments. In the team-based organization, department barriers will not exist, and resources can collaborate to achieve the process targets. Due to the fundamental difference between team-based and function-based structure, both of the organization and the human resource need to be reorganized to match the redesigned processes.

In addition, as companies growing, the growth of organization is a continuous process; therefore, human resource plans of the future project loading are essential for construction companies.

This study demonstrates a team-based human resource planning (THRP) model to determine the maximum project loading of humanpower, and vice versa, to evaluate the required humanpower for the expected project loadings.

2 TEAM-BASED HUMAN RESOURCE PLANNING FOR MULTIPLE PROJECTS

The THRP model consists of four phases to map a company’s processes to the simulation system as shown in Figure 1. Firstly, the new processes model and team-based organization structure are designed in the process reengineering phase. Then, the data preprocessing methods and the simulation algorithms are respectively analyzed and developed. Finally, all results from pervious three phases are integrated in the simulation system. By using the simulation system, the maximal capability of the humanpower, in a work team can be evaluated.

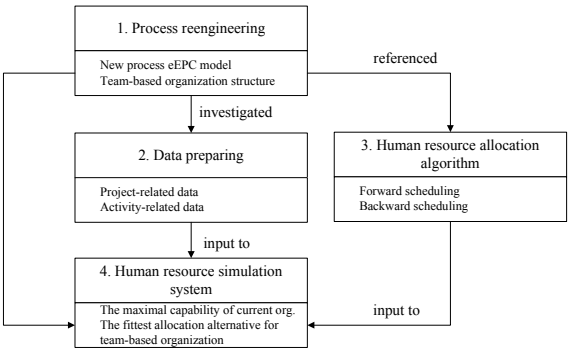

Figure 1. The THPR Model

2.1 Process reengineering

In the THRP, the bases of human resource planning are the rational processes and organization structure. Hence, the first phase of the THRP model is applying BPR philosophy to integrate the organizational functions smashed in different departments into independent, rational, and complete new processes. There are two primary purposes in this phase:

Create original process model: Using process modeling tools to represent the original management processes. As the existing process model has been done, the assessing and redesigning tasks of BPR can be subsequently executed.

Redesign a new process model: Identify the hidden problems of the process and to use the findings as the basis for analysis. A new process model can be drafted in accordance with the analysis of the current management problems of construction companies and establishment of the delivery of the management information technology system.

For these two purposes, this study applies the business process reengineering model addressed by Cheng [4] as shown in Figure 2.

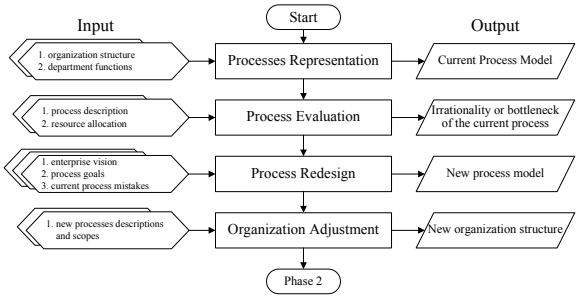

Figure 2. The Stages of Process Reengineering [4]

2.2 Data preparing

To simulate the humanpower performance in the processes, information such as activity duration, humanpower requirement, project loadings, etc., need to be preliminarily examined and analyzed. In this study, the required data of humanpower allocation simulation was classified into project variable and process variable. The project variables include (1) Start time of project, (2) Success Ratio of Biding, and (3) Number of Subcontracts.

On the other hand, the values of process variables differ between original processes and new processes due to changes of task contents or operation methods. Hence, the data preparing procedures of original and new process model are different.

Data preparing of original process variables:

Activity duration with maximal humanpower is an important variable for process simulation. The activity duration is defined as the shortest operation time with maximal humanpower for an activity. According to the investigated results, the activity duration could be simplified as a linear function of the number of workers in an activity; i.e., activity duration will decrease while more humanpower is assigned, but as workers are more than the maximum, the activity duration is not able to be reduced anymore. The variables of the activity durations can be analyzed as following:

(1)Expectation and Variance. Summarize the data, and calculate the Expectation and Variance of durations of all activities in the process.

(2)Goodness-of-fit analysis. The purpose of Goodness-of-fit is to test and verify the fittest probability distribution of duration of an activity. This study used the "Datafit" module in the eM-Plant to verify the fittest function of activity durations.

(3) Schedulable ranges of processes. The schedulable range of process depicts the process duration from the early-start point of the first activity to the last-finish point of the last activity in the process. Except the bidding/contract process, the early-start points of processes are the same with the finish point of their predecessors. The last-finish points of the processes would be the early-start point plus the summarized durations of all orderly activities within the 95% confidence interval.

Process variables of new process model

Due to lack of historical data of new process performance, the investigation rules for data of new process variables are necessary. Per investigating features of activities in new processes, three data collection rules are demonstrated as followed.

Rule 1: The duration of activities in the new process can refer to the same activity in the former process, only if there is no change in the new and former process.

Rule 2: Investigate the total operating time of information system to realize the duration of the activities which are fulfilled with the assistance of information systems, such as Estimation Information System (EIS) applied by this study case.

Rule 3: the spending time of the group decision making or of the EIS operation tasks in the new processes is estimated according to the experiences of executives.

2.3 Human resource allocation algorithm

The algorithm needs to provide the procedure of activity selection and humanpower assignment for the simulation system with considering the nature of complexity of operation at construction companies. Therefore, the project scheduling techniques under human resource constrains with the objective of minimizing project duration are referred; meanwhile, a proper human resource allocation algorithm stands on the multi-project scheduling with heuristic

procedures for searching approximate optimal allocation.
Forward/backward scheduling technique is the primary allocation algorithm, which evaluate the maximal and minimal humanpower allocation of activities.

The Forward Scheduling:
Schedule the activities at their early start times until either available resources or the schedulable activities are exhausted; i.e., each activity whose predecessors are completed and whose resource requirements are met by the currently available resource levels will be taken into the schedulable activity set. Therefore, the maximal resources are possibly assigned to upstream activities to fulfill them as early as possible, and consequently, downstream activities may be accomplished with fewer resources if project duration will not expire.

The Backward Scheduling:
Schedule the activities to just be accomplished at the latest finished times; that is, an activity is schedulable at a current decision time if all of its successors have been completed and its resource requirements can be met by the currently available resource levels. Thus, the minimal resources may be assigned to upstream activities while total remaining time is sufficient to complete the project.

This study addressed their corresponding algorithms as following.

Forward/backward scheduling algorithms:

Input:

P_i /processes set where i= 1,2,3,…,n | n is the no. of processes/

$Proj_k$ /projects set where k= 1,2,3,…,ℓ | ℓ is the no. of projects/

lft_k /the last-finish time of $Porj_k$/

A_{ijk} /activities set where j= 1,2,3,…,m | m is the no. of activities of P_i for $Proj_k$/

m^{ij}_{max} /the maximal humanpower required for j-th activity of the j-th process/

m^{ij}_{min} /the minimal humanpower required for j-th activity of the j-th process/

Output:

mf_{ijk} /the humanpower assigned for j-th activityof P_i for $Proj_k$ by forward scheduling/

mb_{ijk} /the humanpower assigned for j-th activity of P_i for $Proj_k$ by backward scheduling/

Forward algorithm:

From X = 1
Loop until (X ***.equal* to.** m^{ij}_{max})
If (A_{ijk} is fulfilled by humanpower of X) and (the all downstream activities are fulfilled by their minimum humanpower) and (the P_i can be accomplished before lft_k)
Then mf_{ijk} = X
Else X= X+1
End If
End Loop

Backward algorithm:

From X = 1
Loop until (X ***.equal* to.** m^{ij}_{max})
If (A_{ijk} is fulfilled by humanpower of X) and (the all downstream activities are fulfilled by their maximum humanpower) and (the P_i can be accomplished before lft_k)
Then mb_{ijk} = X
Else X= X+1
End If
End Loop

The allocation results of forward/backward scheduling are two extreme scenarios. However, due to constraints of humanpower, the human resource allocation could have conflicts between activities, processes, and projects, so that the enforced idleness owing to the conflicts has to be considered in the THRP model. For identifying the human resource conflicts, an algorithm for checking available humanpower for the scheduling activities is also addressed.

2.4 Human resource simulation system

This study transferred the process context to the mathematical model which is computable to simulate functions of these processes. Therefore, there are six assumptions in the simulation system:
(1)The property values of projects are all derived from the probability distribution functions.
(2)Only human resource is considered.
(3)The sequences of all activities in projects are identified, and the successor can not be started until the predecessor has been finished completely.
(4) A single humanpower can only be assigned to one activity at the current time.
(5) The personnel abilities are set equivalent.
(6) The productivity of an activity is linear functions of humanpower.

Subsequently, this study schemed the development procedure of simulation system preliminarily, where the procedure includes the following steps.

Step1. *System analysis*
This summarizes the results of other three phases and creates the system scenario that guides simulation of every new process of a company. Therefore, process

descriptions and system runtime procedures are two parts of system scenarios.

The process description provides the scenario of process simulation in the system. That is, the description includes process scope, activities, number of team members, and probability distribution function (pdf) of enable event occurrence of one process. In addition, a set of humanpower allocation alternatives should be derived under the limitation of available human resource.

On the other hand, the system runtime procedure describes the mechanism for choosing the fittest human resource allocation from the set of humanpower allocation alternatives, and it also illustrates the mechanism for determining the maximal project loading of humanpower. Figure 3 shows the system runtime schedule.

Step2. Fitness assessing indexes determination

According to the problems definition, this study uses the "humanpower idleness" index which expresses the efficiency of the human resource to evaluate the fitness of each allocation alternatives. Meanwhile, the simulation progress will not be finished until all the project loadings can not be fully accomplished by the available humanpower.

Step3. Simulation system creation

This study uses the object-oriented simulation software named "eM-Plant" to simulate the possible allocation alternatives. The tasks in this step include : (1)system objects model creation, (2)objects allocation, (3)object attributes defining and values setting, (4)control method programming, (5)output defining. As they have been done, the relevant objects in the MainFrame module of eM-Plant corresponding to the process model is shown in Figure 4.

Step4. System test

This research constructed an existing process model additionally, and also simulated it with the simulation model to compare the simulation results with the corresponding parameters in the real existing process. If the errors are acceptable, we can say that the simulation model is correct to represent the real system.

Step5. System application

As the simulation model has been verified, aiming at new processes, this step applies the model to evaluate the maximal project loading of the existing humanpower, and to create the combinations of humanpower and project loadings, which are references of human resource planning while business achievement of a company is changing in the future.

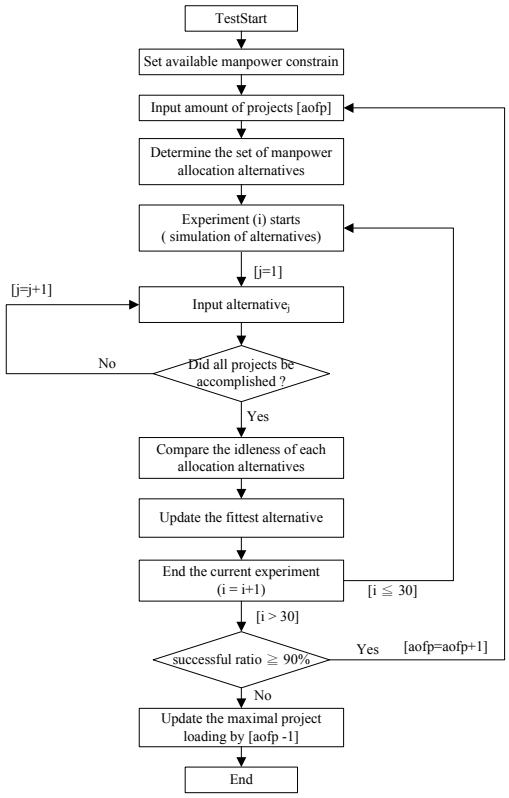

Figure 3. System Runtime Procedure

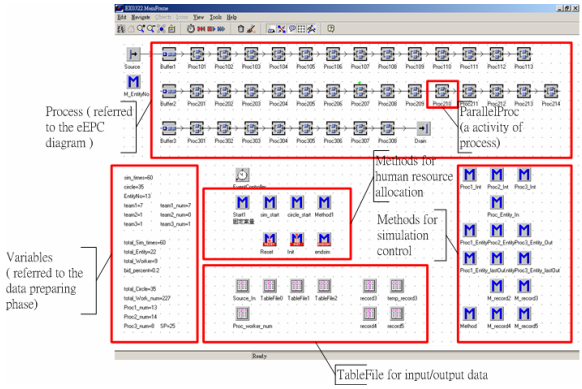

Figure 4. The Objects Allocation in the Simulation Model

3 CASE STUDY OF THRP

A real case of construction company "A" with intention of business process reengineering project is illustrated in this section. This study applies the THRP model to assist company "A" with reengineering the project planning process and evaluating the rationality of human resource for the new-designed process.

3.1 Process Reengineering Phase

Figure 5 shows the organization structure of company "A". Due to ineffectiveness of project planning, the manager firstly chose the project planning process for reengineering, where the planning process was executed separately by

bid/contract division, estimate division and purchase division in the engineering department.

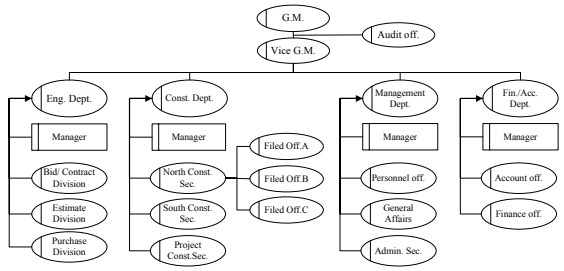

Figure 5. The Organizational Structure of Company "A" before BPR

Based on the functional organization structure of company "A" as shown in Figure 5, a project planning process was entirely executed by the engineering department, but was divided into three functional task divisions. Therefore, the process was separated into three operational categories. As executives have decided to accept the invitation for bidding of a construction project, the planning process will be enabled and be split into (1) bidding/contracting, (2) estimation/budget and (3) purchasing functional tasks, which are executed by their corresponding divisions.

Per discussion and brainstorming with senior managers, this study asserted the hidden problems within the original bidding/contract process as following:

(1) Only quantities survey was implemented with the computer-aided software while all the other activities were finished manually.
(2) The job loading was not proportioned to the task divisions due to a various magnitude of construction projects.
(3) No valid history reference data of material and labor to assist estimators so that the cost estimate didn't correspond with the ruling prices.
(4) The duration of the document circulation increased unexpectedly because all documentation had to be approved by the managers.

According these four defects, a new process model was then created. In particular, because information can be the "glue" that holds an organizational structure together [3], a cross-functional information system of engineering information system (EIS) was applied. Hence, some activities can be integrated and executed by EIS. Moreover, the approval activities, such as "review bidding examination reports" and "survey quotation tables" which are irrelevant to the objective of process, were superseded, and the decision making activities were also delegated to the decision group. Consequently, the existing bidding/contract process was integrated into a shortened and efficient new process.

Figure 6 shows the team-based organization structure of company A corresponding to the new project planning processes. The primary differences between the former and the team-based structure are the formations of the decision group and the engineering project teams. The engineering project team, which combines cross-functional skills, is responsible to entire project planning process.

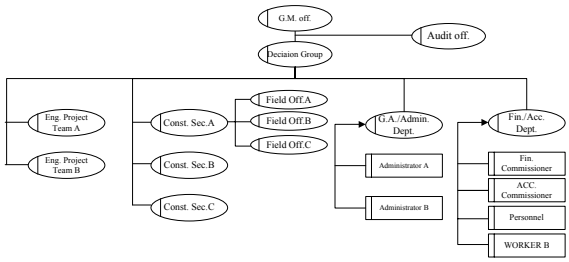

Figure 6. The Organizational Structure of Company "A" after BPR

However, due to lack of teamwork experience, the rational humanpower of a team is difficult to estimate.

3.2 Preprocessed Data

In the data preparing phase, the values of project variables and process variables were estimated.

Project variables:

(1) Start time of project. For company "A", projects began irregularly, so "Uniform Distribution" is applicable to characterize the start point of a project. In other words, projects are assumed to be enabled with equal probability in every month.
(2) Success Ratio of Bidding. By counting the successful times of historical bidding data, the ratio of successful bidding of company "A" is set at "20 %".
(3) Number of Subcontracts. Based on the historical data of company "A", eight projects had been finished sequentially from May 1999 to October 2000, and the number of subcontracts of each project is counted in the range from 20 to 36 with an average of 25.

Process variables

The process variables of both original and new-designed processes were estimated. In the estimated results, activities with their humanpower, probability distribution functions, and durations with up-boundary of 95% confidence interval are evaluated.

3.3 Human Resource Simulation

This study takes the "project planning process" of the company "A" as an example in this section. After a model test with the original project planning process, the results of maximal project loading and average humanpower idleness match the real situations.

After model test, new-designed project planning process is finally modeled in the eM-Plant system, and evaluated with two criteria: (1) the number of members of engineering project team is a constant of seven, which is total humanpower of the engineering

department; (2) take the number of team members as an independent variable for the maximum project loading, by which the combinations of humanpower and project loading can be estimated.

For the first simulation criteria, Figure 7 shows the allocation alternatives.

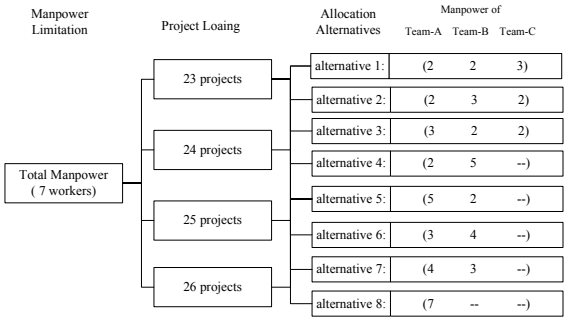

Figure 7. The Humanpower Allocation Alternatives Tree of The Engineering Project Team

With applying the forward scheduling method, the success ratio was always higher then 90% while the project loading was under 25 projects, and it decreased to 83 % (less then the threshold of 90%) as the loading increased to 26 projects. Therefore, the maximum project loading of seven members is evaluated 25 projects. Likewise, as the backward scheduling method was applied, the success ration was always higher then 90% as the project loading was under 40 projects, and it would decrease to 80 % as the loading increased to 41 projects. Therefore, the maximum project loading of seven members is 40 projects while the backward scheduling method was applied.

Because the forward scheduling deploys the maximum resource at the beginning of a project to accomplish the process as soon as possible, the capability of humanpower might be limited by the more resource conflicts than that in the backward scheduling method. Therefore, this research speculates that the common project loading is between the two above referenced extreme cases. Based on this corollary, the margin of company A's manpower was adapted to 25 of minimum to 40 of maximum projects.

For the second criteria, we extended the humanpower limitation of the engineering project team up to 15 workers to simulate the possible growth of the organization, and estimate their corresponding capabilities. The simulation results are shown in the Figure 8. From Figure 8, we can find the project loading range of one specific humanpower limitation simulated by the system, which can be a reference for determining whether the project loading matches to the humanpower. Thus, managers could estimate the efficiency or requirement of humanpower based on the number of projects.

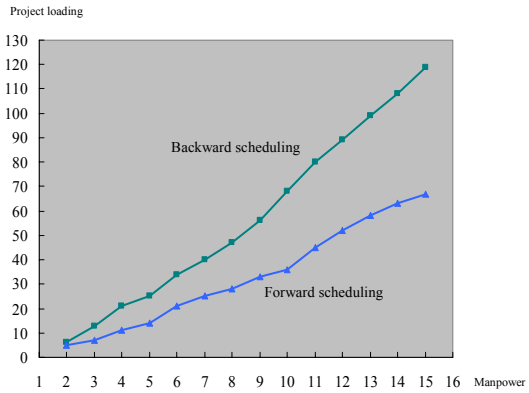

Figure 8. The Humanpower Capability Curves of The New Project Planning Process

4. CONCLUSION

This research addressed the team-based human resource planning model to facilitate human resource allocation for process reengineering. With the THRP model, the maximal project loading of existing humanpower could be evaluated; moreover, the relations between project loading and the maximal humanpower were also created based on the new-designed processes. Finally, the conclusions of this study are addressed as following：

(1) This study implemented the human resource allocation algorithms of the forward/backward scheduling methods with the eM-Plant simulation system, and the results have been verified that the process model in simulation system is close to the reality.

(2) The results of the simulation model illustrate the different efficiency of the humanpower operation between the existing and the new processes. This infers that the integration of the cross-functional processes and the human resource caused by the process reengineering would increase the performance of one enterprise.

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GIS-BASED ROADWAY CONSTRUCTION PLANNING

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Roadway construction planning processes involve a large amount of information regarding design, construction methods, quantities, unit costs, and production rates. GIS (Geographic Information System) is a very effective tool for integrating and managing various types of information such as spatial and non-spatial data required for roadway construction planning. This paper proposes a GIS-based system for improving roadway construction planning by integrating design and construction information. The proposed system can also help construction planners make a proper decision in a unique way with its 'Interactive Planning' function that supports the space scheduling and activity sequence visualization processes.

Keywords: GIS, Construction planning, Information integration, Space scheduling

1. INTRODUCTION

Roadway construction planning processes involve a large amount of information on design and construction. GIS (Geographic Information System) is a strong tool for integrating and managing various types of information such as spatial and non-spatial data required for roadway construction planning.

The roadway design process has been improved greatly by using CAD/CAE tools. Therefore most design data are created and stored electronically. However, the digitized design data have not been fully utilized for construction planning purposes. In recent years, in the architectural engineering field, there has been lots of improvement in integrating design and construction information for using design data at construction planning stage [Yau 1992 ; Marir et al. 1998 ; Koo and Fischer 2000 ; Cheng 2001]. Attempts to utilize the digitized design data for construction planning was also taken up in civil engineering field recently [Hassanein and Moselhi 2002].

A GIS-based system for improving roadway construction planning is presented in this paper. The proposed system supports the roadway construction planning with 'Information Integration', 'Spatial Analysis' and 'Visualization' functions. The application of the proposed system is limited to road construction among the highway construction components that include roads, bridges and tunnels.

2. GIS-BASED INFORMATION INTEGRATION FOR ROADWAY PLANNING

The roadway construction planning system proposed in this paper is based on integrating design and construction information within a GIS environment. The overall structure of the system and the methodology of integrating information are explained in this section.

2.1 Overall Structure

Figure 1 shows the overall structure of the proposed system. Two dimensional CAD drawings are converted to several shapefiles which are a type of GIS formatted-files according to geometry such as points, lines, and polygons. The converted shapefiles contain spatial feature attribute table with the conventional feature attributes and the shape features. The spatial feature attributes are integrated with the non-spatial attributes including construction information such as activity assemblies, unit costs, and production rates by the system's 'Interactive Planning' capability. The system then generates a table containing the quantities, the costs, the activity lists and their durations. This table can be transferred directly to a commercial scheduling software. After detailed scheduling (e.g. calculation of early start date and early finish date etc.) based on the data in the table with a scheduling application program, the date information is returned to the system and connected to the corresponding

construction elements by the system. The system then can visualize the construction sequence.

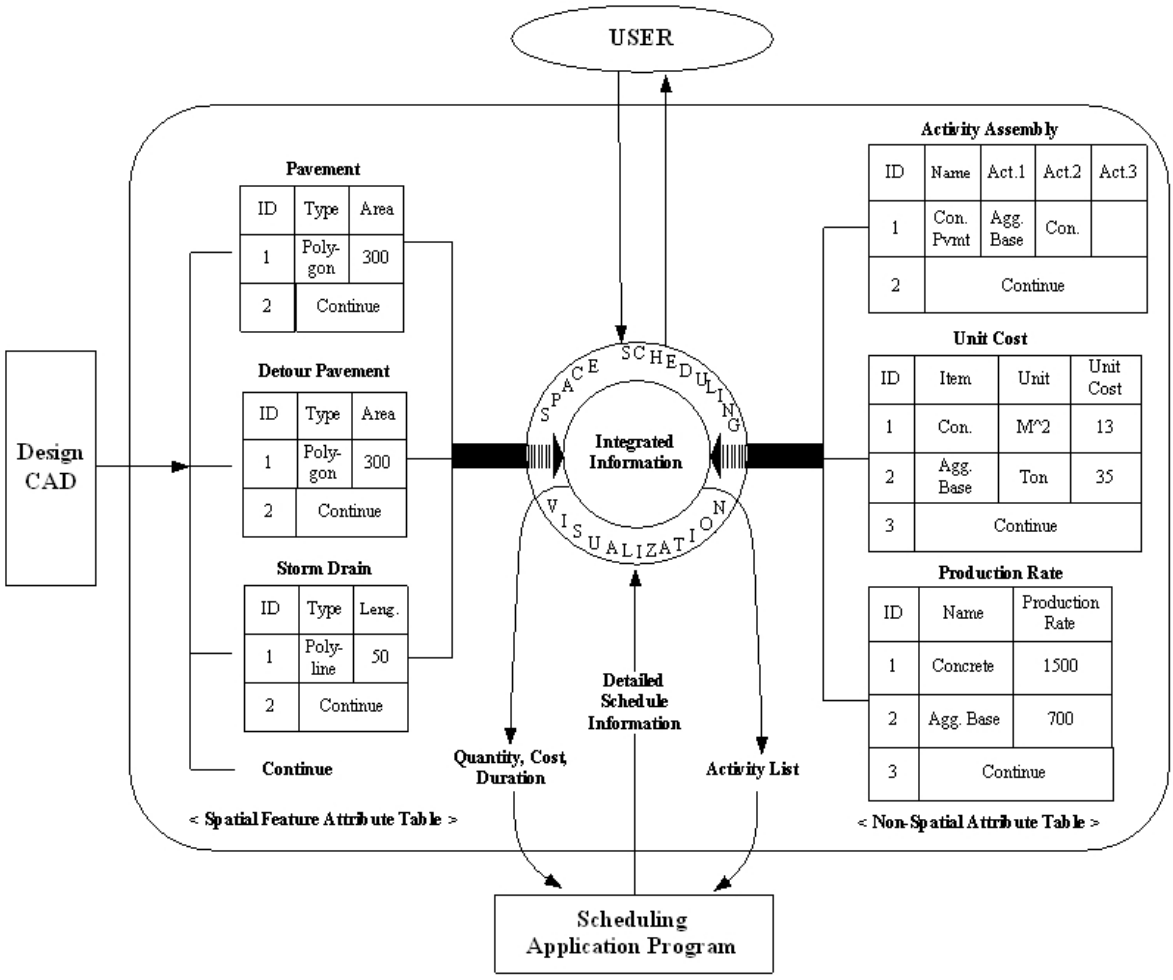

Figure 1. Information Integration Structure of the System

2.2 Classification of Construction Elements Based on Geometry

Table 1. Classification of Construction Elements

Work Section	Shapefile (Construction Element)	Geometry
Pavement	Pavement	Polygon
	Detour Pavement	Polygon
Earthwork	Cut/Fill boundary	Polygon
Drainage	Culvert	Polyline
	Pipe	Polyline
	Gutter	Polyline
	Inlet/Outlet	Point
	Manhole	Point

As shown in Table 1, the roadway construction is composed of three work sections, 'Pavement', 'Earthwork', and 'Drainage'. The construction elements of the work section are classified and stored in separate shapefiles according to their geometry. For example, pavement area on design CAD drawings is converted to a shapefile and named 'Pavement'.

The spatial attribute tables including the location and geometric information about each shape are automatically generated on converting to GIS-formatted shapefiles. The tables contain both the conventional feature attributes such as object id, area, and length etc. and the shape features such as the coordinates of the shape components. This data is the base materials for quantity take-off [Seo et al. 2002].

2.3 Non-Spatial Attribute Table

Additional data not included in the spatial attribute tables are required for calculating quantities, costs, and activity lists. The non-spatial attribute tables are composed of 'Activity Assembly' for each construction element, 'Unit Cost', and 'Production Rate'. The activity assembly table contains the detailed activity lists associated with graphic objects of the shapefiles. For example, as shown in Figure 1, the polygons of graphic objects which represents 'Concrete pavement' have two activities: 'Aggregate

Base' and 'Concrete'. These two activities are included in the activity assembly table to generate necessary activity lists for selected graphic objects.

2.4 Information Integration Process

Spatial data and non-spatial data are integrated by the customized module in ArcMap Visual Basic Application. A selected graphic object by the planners is connected to one of construction elements with an activity assemblies. The system aids the process with various construction element options so that the planners can easily connect the graphic object with proper non-spatial attributes.

The detailed data like unit costs and production rates in the prepared non-spatial attribute tables are used for estimating cost and duration of activities. All of the generated information is allocated to a new table. Figure 2 represents the process of quantity take-off, cost estimation, and calculating duration of activities. Activity lists generated can be directly transmitted to a commercial scheduling application program. After detatiled scheduling with the commercial scheduling software, the start and finish date information is returned to the system. This information is added to the spatial attribute table so that the visualization of the activity sequence can be achived.

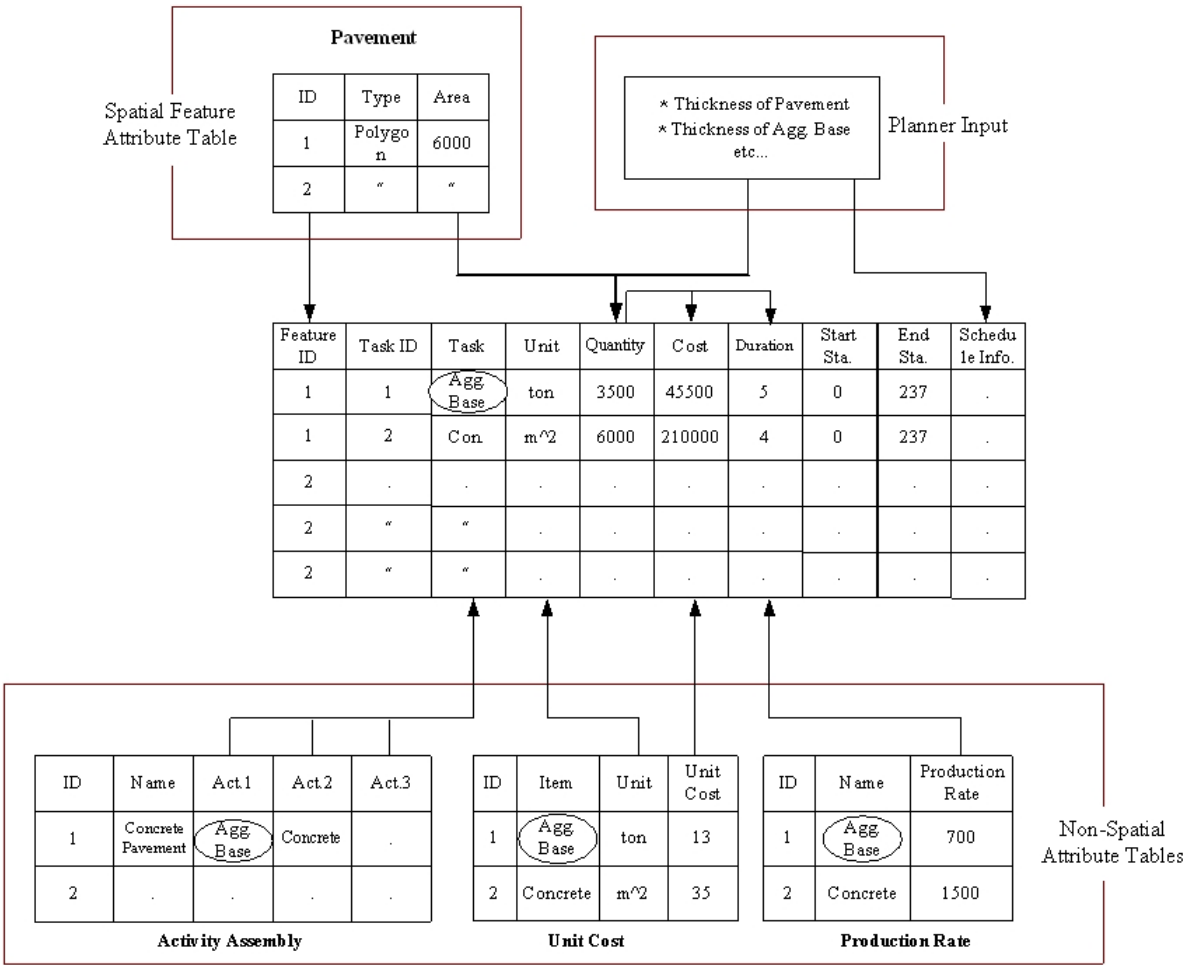

Figure 2. Data Flow

3. INTERACTIVE SPACE SCHEDULING

3.1 Space Scheduling & Activity Lists Generation

Architecture buildings are easily modularized into construction elements like columns, beams, and windows etc. However, roadway design components are not. The proposed system therefore provides the planners with 'Interactive Space Scheduling' function by which the planners modularize the design component in real time. After activating an interesting shapefile such as 'Pavement', the planners can divide graphic objects directly in real time. Then the system identifies the intersected region as a new graphic object, which means, as shown in Figure 3, it is possible that the system generates activity lists, quantities, and costs by connecting the divided graphic objects and non-spatial attributes. This function has an important meaning in that the planners are able to divide 2-D roadway graphic

objects in real time and directly connect them with construction information to create the activity lists for the modularized construction elements.

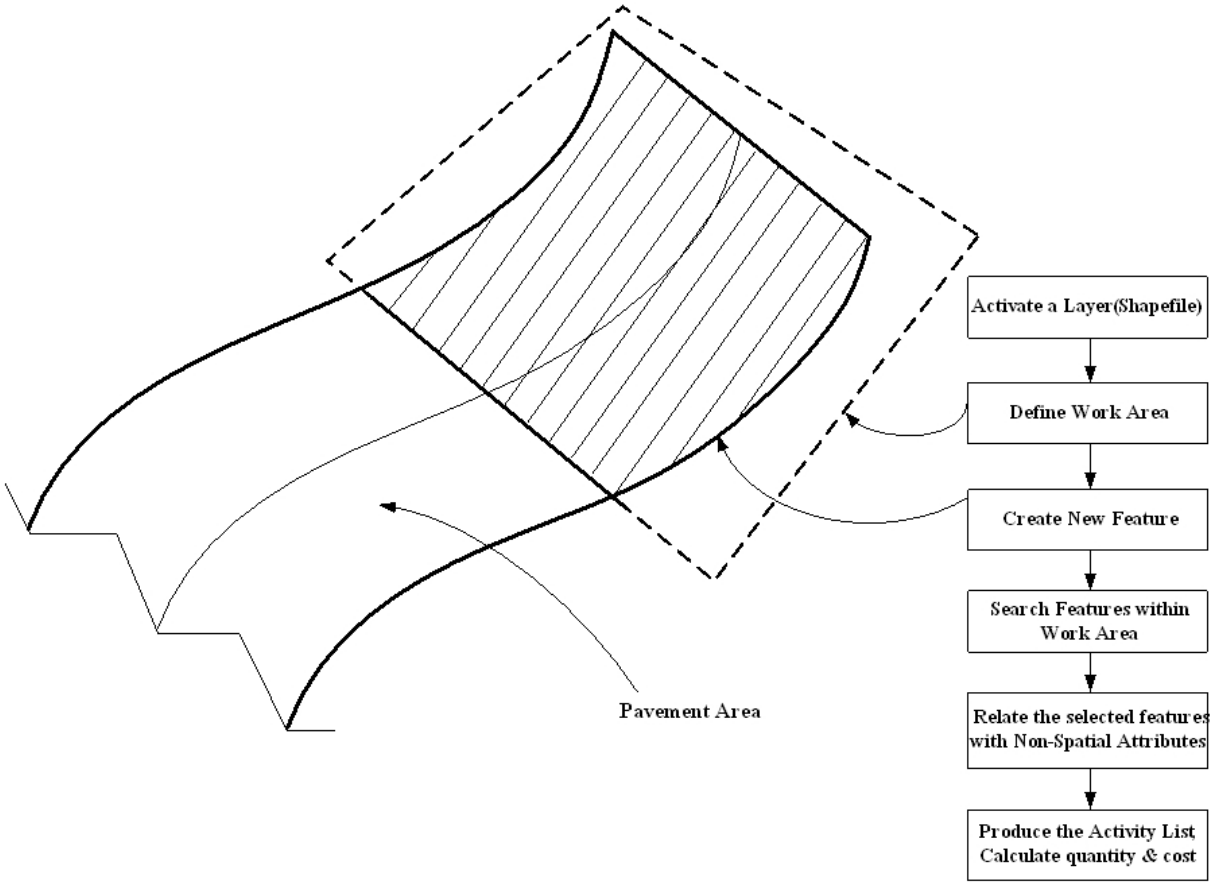

Figure 3. Space Scheduling Function

3.2 Interaction with Scheduling Application Programs and Visualization of Activity Sequences

The activity lists obtained through the process mentioned above are sent to a scheduling application program to complete detailed CPM scheduling. After that planners can get a detailed schedule table including the start date and the finish date. This detailed schedule table is connected again to the graphic objects by the system so that planners can visualize and analyze activity sequences. The system demonstrates activity sequences by changing the color of graphic objects. Planners can review the sequences immediately and intuitively, if there is something wrong with the sequences, planners can modify the detailed schedule in real time.

4. OTHER SYSTEM FEATURES

This on-going research effort at Hanyang University also includes the development of the following system features to help planners plan roadway construction.

4.1 Using aerial photographs

Arial photographs are utilized so that the planners can have the visual feedback on the construction site and the surrounding area while he/she is planning the roadway construction work with the system. The photographs are overlaid with the GIS spatial feature data. While the spatial and non-spatial data of the planning system provide the planners with the various helpful information, it was also found that the immediate and intuitive understanding on the site could be obtained by presenting the site condition through the photograph along with the spatial and non-spatial data of the proposed design work and the existing features.

4.2 Operation Level Planning

The system provides the route analysis and the equipment selection functions for the operation level planning. The planners can identify the best route from the construction site to the dump and/or loading site by comparing the distances between two points or by comparing the time required to destination.

Besides, the best combination of equipment (e.g. dump trucks and loading equipment) can be calculated based on the cycle time of equipment.

4.3 Temporary Road Design

Temporary roads for equipment's entrance to the construction site are often required. In this case, planners can design temporary roads with the system based on the analysis of the digital terrain model as well as the information provided by the spatial/non-spatial features and the visual feedback on the construction site. The system helps planners design temporary roads with its design tools.

5. SYSTEM IMPLEMENTATION

The proposed system in this paper was developed by customizing ArcGIS which is one of GIS application programs. The customized module for information integration and visualization was designed with 'Visual Basic for Application' which works as an integral component of the desktop ArcGIS applications with ArcObject library [ESRI 2001]. The GIS tables such as 'Activity Assembly', 'Unit Cost', and 'Production Rate' are also made on ArcGIS. MS-Project was used for detailed scheduling. Figure 4 is a schematic diagram explaining the system implementation processes.

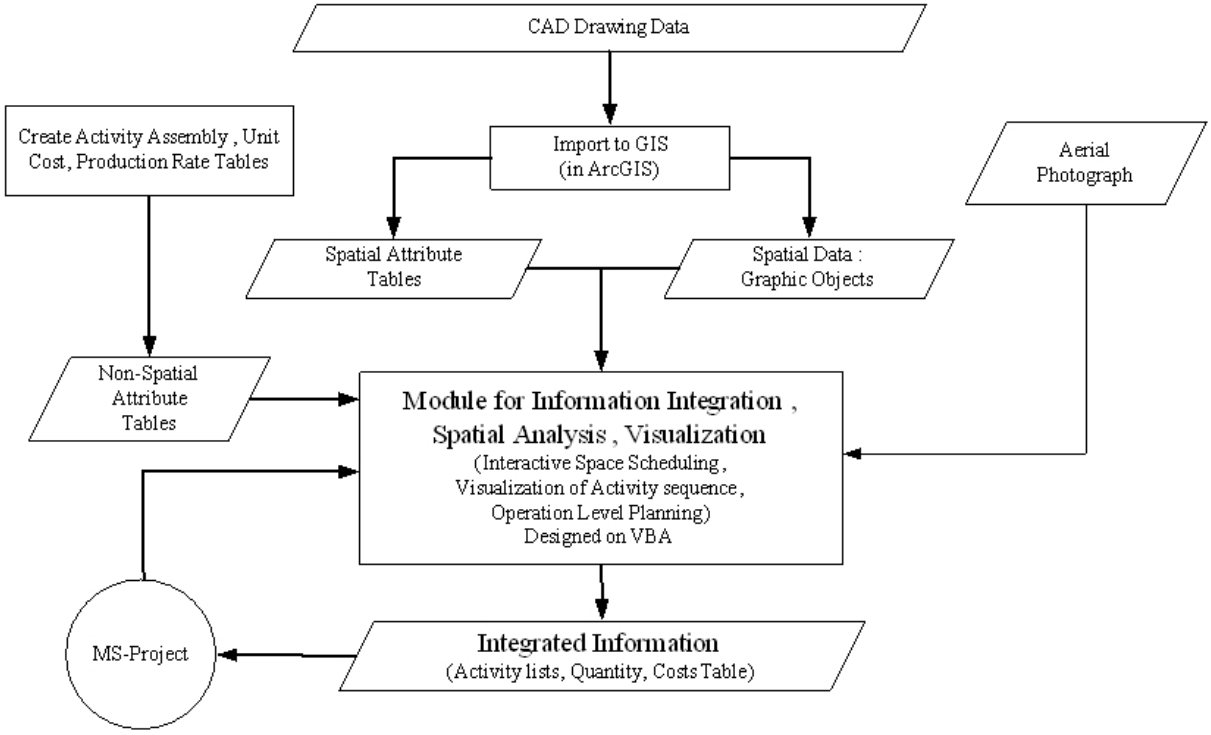

Figure 4. System Implementation

6. CONCLUSION

The proposed system in this study could improve roadway construction planning processes based on the information integration, the spatial analysis, and the visualization. The system provides construction planners with 'Interactive Space Scheduling' function with which the planners can divide 2-D roadway graphic objects not modularized into modules flexibly and integrate design information and construction information in real time. The system not only generates activity lists and calculates activities' costs and duration, but also visualizes activity sequences. Besides, the system performs the operation level planning through the route analysis and equipment selection features. The application of the proposed system is currently limited to the roadway portion of the highway construction projects. It is hoped that in the future the application of the system features extend to the structures such as bridges and tunnels.

Acknowledgments

The authors wish to acknowledge the financial support of Construction Research Institute, Hanyang University.

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PLANNING AND MONITORING THE TACT OF WORK FLOW

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Abstract: To ensure a continuous and smooth work flow, this research proposes (1) Tact Scheduling Method as an alternative to traditional ones and (2) Work Flow Monitoring System (WFMS). Tact scheduling is intended to balance the unit activities of relevant work trades in terms of the duration and the labor input required for performing each activity. Subcontractors as well as the main contractor participate in the planning stage and adjust the same duration and the labor input for every unit activity by zoning the workspace. Prior to developing the WFMS, a few factors that are considered to possibly affect the variation of the work flow are defined and indicators to measure these factors are devised.

Keywords: Tact, Work Flow, Scheduling, Planning, Monitoring.

1. INTRODUCTION

As the buildings are become larger in size and taller, the aspect of time consumed for constructing buildings are now the most important factor to be considered in the planning stages. Among the various kinds of works involved in a building construction project, the finishing works need to be managed more carefully, since these works are very complex and at times are in conflict with themselves. One research by KICEM [1] reported that the duration for finishing works in Korea is much longer than those of other countries and that there is a need to develop a more effective management system for finishing. This is summarized in Table 1.

In order to reduce the time consumed for the finishing works in building construction, it is necessary to understand the characteristics of the finishing works such as the tact or rhythm of such works flow. This is also related to management of the cycle time of the finishing works. The impact of work flow variations and the importance of managing the work flow are well described in the Parade Game [2]. An efficiently and systematically predefined work space and crews for each works in that space enable the works processed in a given duration to be conducted in a controlled manner. This consequently minimizes the impact of flow variation.

The objectives of this research are two-fold: one is to explain the concept of tact schedule management method through a sample case study. This is not a new method in that it is a re-emerging concept as a schedule management tool due to the growing importance of work flows. This method is

Table 1. Comparison of building construction duration

Project Name		Floors		Total Duration (Month)	Earth Work Duration (Month)	Structural Work Duration (Month)	Finishing Work Duration (Month)
		Under Ground	Above Ground				
USA	Allied Bank	B4	71	30	9	15	6
	Hines	B2	53	23	6	12	5
	US Steel	B3	64	30	12	13	5
Japan	Landmark Tower	B4	70	37	11	20	6
	World Trade Center	B3	40	32	13	13	6
	Kobe Trade Center	B2	26	24	7	9	8
Korea	Big Way Tower	B7	21	29	7	12	11
	Bumcheon Bldg.	B5	25	29	7	13	19
	Dongyang Bldg.	B7	21	29	7	10	12

* Finishing work duration is measured after completion of structural works.

particularly discussed in connection with the management of repetitive construction works. The other objective is to present a concept for work flow monitoring system. This system is devised to monitor the work flows scheduled by using the tact schedule management method. Some variables, mainly related to labor factors, are suggested as indicators of work flow monitoring. The main focus of this paper is on the finishing works of building construction, since this kind of works is very repetitive and so, the tact of work flow shall be said to be more important compared to other works.

2. CURRENT SCHEDULE MANAGEMENT PRACTICES

The finishing works of multi-story building or high-rise building construction works are repetitive. These works are composed of activities that are of relatively smaller in work size but more in number than other works such as structural or earth works, and thus are normally executed by various subcontractors. Therefore, the managing approach should be different from that of structural or earth works. The main points in managing these works can be summarized as (1) the continuity of work flow and (2) the stability of resources in accordance with the work flow. In this regard, the current schedule management approach shall be said to have certain limitations as descried below: (1) Due to the insufficient consideration on productivity of each trade, the work flows among various trades are not being managed effectively. (2) An investigation on case projects has shown that there are many of idling time at the finishing work stages, which take up almost 45% of the finishing works duration. Most importantly, this idle time is due to the poor work flow as well as the instability of resources. (3) Discontinuous flows of repetitive works are also one of the reasons for the loss in productivity, since it reduces the possibility of increasing productivity through the learning effect. (4) Discontinuous work flow causes the problem of miscommunication among trade contractors, which resulted from poor communication network. This, in turn, negatively affects the work of the main contractor [3].

In addition to the problems mentioned above, the limitations of the critical-path method (CPM) in being applied to repetitive works are well described in the previous researches and can be summarized as follows: (1) It is not practical to consider the flow of works first and then attempt to control the variation of work flow by CPM. (2) CPM is more appropriate for long-term planning rather than for detailed task level planning. (3) Constraints of each activity are hardly reflected on CPM networks [2][4].

Another widely used schedule management tool is the line-of-balance (LOB) method. This is relatively efficient for repetitive works such as the construction of high-rise building, but it also has some limitations such as: (1) it is difficult to change the pace of activity or productivity from its initial setting and (2) it lacks the consideration of individual activities and their flows.

In order to overcome these problems, more attention should be paid on work flow and stability of resources during the development of construction schedules. In this regard, one of the effective scheduling techniques is the tact system or the so-called tact schedule management method.

3. TACT SCHEDULE MANAGEMENT

3.1 What is tact schedule management?

Major Japanese construction companies like Taisei have already adopted the tact system or tact schedule management method in the early 90s [5]. At that time, however, there was a lack of understanding in the concept of work flow or the stability of resources. In 2001, a major Korean construction company, Samsung Engineering & Construction, combined the tact system with the principles of lean construction [6]. In order to understand tact schedule management system, there are a few key concepts that need to be known first, as shown in Fig 1[7].

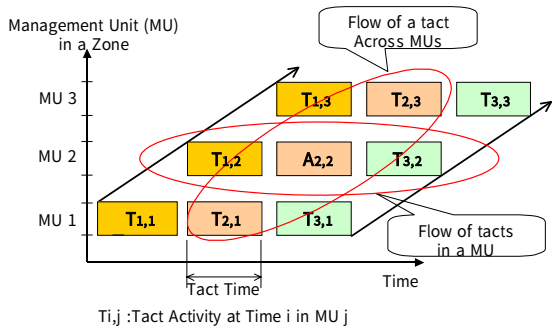

Fig 1. Key Concepts of Tact Schedule Mgmt.

1) Management Unit (MU)

This is the management unit based on workspace. In a multi-story building construction, a floor or a divided workspace in a floor shall be one unit. Each management unit will have the same work pattern. In addition to management unit, there are zones as well. A zone is a set of management units. For example of an apartment construction, a floor can be divided into two zones; public zone including elevator hall and private zone including residential units.

2) Tact Activity

This is one unit of activity or an element of network of works in a management unit. Each tact activity is executed sequentially in a management unit. A building construction can be described as a network (or flow) of management unit and each management unit can be described as a network of tact activity.

3) Tact Time

This is the duration of a tact activity and every tact activities. In tact schedule management, tact time

should be constant so that the entire tact can flow continuously. In other words, tact activities are executed in a synchronized manner at one time point. For tact time to be constant, the resources for tact activities should be well organized and stabilized.

3.2 Tact scheduling process

The general process for tact scheduling is described in Fig 2. Here, the main-contractor as well as sub-contractors is involved. In addition to this, monitoring proper indicators that show the performance of tact schedule management is important. This is an example of continuous improvement of schedule management.

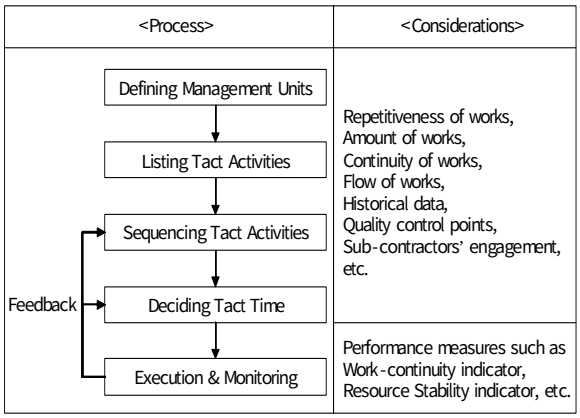

Fig 2. Process of tact scheduling

3.3 Tact schedule of a case project

The case project includes three blocks of building. In each block, underground parking garage and commercial facilities are positioned from LG4 to L2 or L1. Areas from L2 or L3 of each block are composed of total 142 units of apartments. The project team's efforts on tact scheduling in accordance with the process proposed above can be described as follows: (1) Work zones are divided into elevator hall zone, residential unit zone, and bath room zone in the residential units. Management units are defined by each zone on every floors of a building block. For example, residential unit zone on 12^{th} floor of block 102 becomes an independent management unit. (2) Tact activities are categorized into 26 tact activities for residential unit zone, 15 for bath room zone, and 10 for elevator hall zone are listed. (3) The listed tact activities are sequenced according to the predecessor-successor logics and tact time is set as 4 days considering the productivity and work amount of each tact activities. (4) A set of performance indicators are developed by the research team. These indicators are to monitor the effectiveness of tact schedule management and include Worker Loyalty (WL), Labor Resource Stability (LRS), and Work Flow (WF). These indicators form the basis for the development of work flow monitoring system, which will be further described in the following chapter.

Fig 3 is a part of the graphical presentation of the tact schedule developed for residential unit zone of block 102 of the case project. The finishing works duration of the case project was scheduled for 8 months. This is still longer than that of other countries, but quite shorter than other projects in the Korean building construction market.

4. WORK FLOW MONITORING SYSTEM (WFMS)

4.1 Key indicators for work flow

1) Basic assumptions

In order to achieve a performance goal, management must focus on controllable factors that affect the result among other issues. From this point of view, labor-related controllable factors are significant in achieving a continuous work flow in the repetitive construction work presented in Fig 3, since this type of work is considerably labor dependent. Therefore, a relationship among labor factors and work flow should be identified empirically so the managers can control the factors effectively.

A stable supply of quality labor is a common issue in construction projects. Quality labor means stability in providing skilled labor that possesses a certain level of skill. When the skill supplied for a trade is maintained at an acceptable level, the frequency of worker changes or stability of labor resource becomes a concern. That is, the instability of labor resources leads to deviations from normal workflow, and thus, the following hypothesis can be made.

H1: Labor Resource Stability will affect Work flow

One of the most fundamental causes of variations in achieving a target schedule is human factors, e.g., workers absenteeism or worker loyalty. Poor worker loyalty increases the possibility of schedule overruns, deviations from the normal work flow, and instability of labor resource. That is, worker loyalty is somehow related to workflow and labor resource stability. Therefore, the following hypotheses can be made.

H2: Worker Loyalty will affect Work flow

H3: Worker Loyalty will affect Labor Resource Stability

2) Measures for the key indicators

Work flow (WF)

From the standpoint of the contractor, the continuous work flow is an important success factor in terms of achieving project management goal. According to the planned schedule of the case project, waiting time should be constant or zero until moving to the next tack activity. However, in reality, irregular waiting time can occur. The measure of work flow in this research is the waiting time ratio (WTR). WTR is the ratio of 'the waiting time between any two consecutive activities' to 'the available working time' for a given period, and is calculated using Eq. (1). In

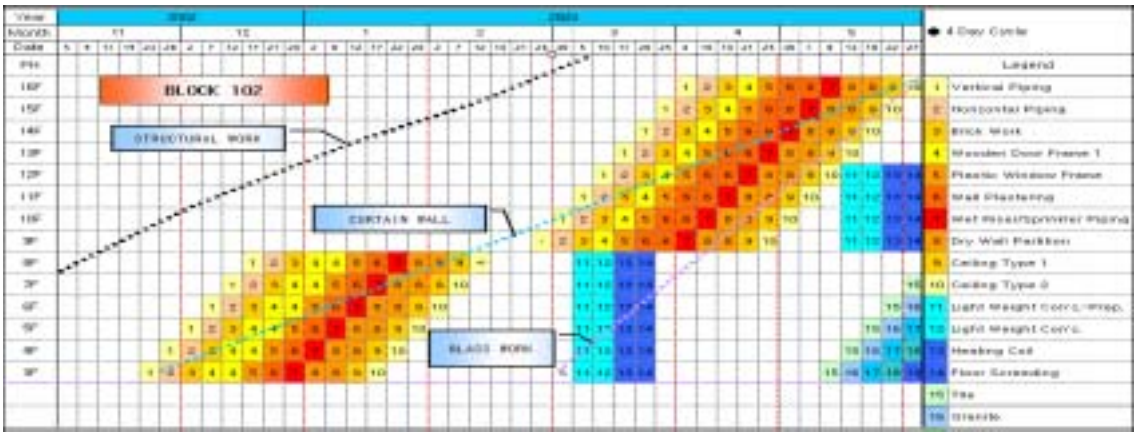

Fig 3. Parts of the tact schedule of the case project

the case study, WTR was measured at the sub-contractor level.

WTR = (Waiting time for a given period) / (Available working time for a given period) (1)

Labor resource stability (LRS)

When the planned schedule is developed, it is assumed that labor resource will be provided stably in terms of quality and quantity. However, during the construction process the number of workers on a trade varies from day to day and even the individual workers change. The measure of labor resource stability in this research is the worker change ratio (WCR). WCR is the ratio of 'the number of workers changed from the previous day' to 'the number of workers on the day', and is calculated using Eq. (2). In the case study, WCR was measured at the sub-contractor level.

WCR = (Nos. of workers changed from the previous day) / (Nos. of workers on a certain day) (2)

Worker loyalty (WL)

When the planned schedule is developed, worker loyalty is assumed to be quite consistent. However, absenteeism often occurs, and this has an effect on the overall project. The measure of worker loyalty in this research is the worker attendance ratio (WAR). WAR is the ratio of 'actual working days for a given period' to 'available working days for a given period', and is calculated using (3). In the case study, WAR was measured at the individual worker level and averaged at the sub-contractor level.

WAR = (Actual working days for a given period) / (Available working days for a given period) (3)

3) Verification of the key indicators

The verification of the key indicators suggested in this research is two fold: one is to confirm the content validity of the indicators and the other is to verify the relationship among the indicators in an empirical way.

Content validity

The purpose of content validity is to check if a measure or an indicator reflects the specific intended domain of the content. In other words, it is necessary to confirm that WAR, WCR, and WTR actually represent worker loyalty, labor resource stability, and workflow, respectively. The content validity was confirmed through 3~6 times of interviews with experts including four professors from universities, six managers from a construction company, and seven researchers from graduate schools.

Relationship among the indicators

To confirm the relationship among the indicators, raw data were collected from seven sub-contract works, on a daily basis over a four-month period from the case project. The indicators were computed on a monthly basis at the sub-contractor level, due to the program of the company job reporting system. A statistical analysis was also done at the month level. The correlation matrix of the indicators, as shown in Table 2, confirms that there are statistically significant correlations among the indicators.

Table 2. Correlation Matrix of Variables

	WL (WAR)	LRS (WCR)	WF (WTR)
WL (WAR)	1.000	–	–
LRS (WCR)	-0.744**	1.000	–
WF (WTR)	-0.562**	0.606**	1.000

** Correlation is significant at 0.01 level (2-tailed).

4.2 Conceptual model of WFMS

In order to control the tact schedule, a conceptual model of work flow monitoring system is presented in Fig 4. This model is based on the indicators and assumptions explained above. When the WTR is greater than one, it can be said that the work flow is out of control and thus further examination is required to find out the possible reasons in terms of the LRS and the WL. The WTR which is less than or equal to one implies that the work flow is controlled as scheduled. When the WCR is greater than zero, it can be said that the current labor resource is unstable and thus a proper action should be taken to control the labor stability. The WCR which is equal to zero implies that the current labor resource is supplied in a stable manner. When the WAR is less than one, it can be said that the worker's attendance is facing problems and thus a proper action should be taken to improve the labor loyalty. The WAR which is equal

to one implies that the current labor loyalty is at the acceptable level.

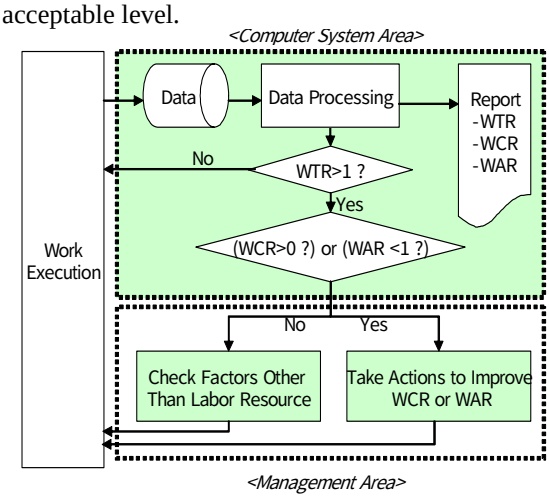

Fig 4. Conceptual model of WFMS

4.3 Implementation of WFMS; S-SMART

A computer system named S-SMART (Samsung Site Monitoring, Assessment and Reporting for Tact management) was developed for work flow monitoring in the case project. This system has two main functions: one is to monitor the work flow as explained above, and the other is to monitor the progress of works planned by the tact scheduling method as shown in chapter 3. Fig 5 below shows the development framework of S-SMART. As an illustrated example, the major functions of S-SMART are shown in the following paragraphs.

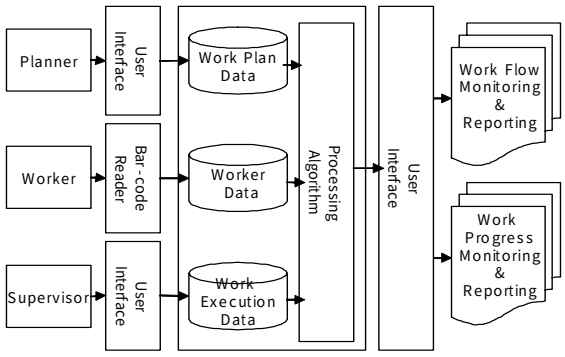

Fig 5: Development framework of S-SMART

Establishing the tact schedule by planners

After the basic planning of tact schedule, the schedule information is input into the system. The key information to be input are MU, tact name, tact time, sub-contractor, input labor quantity, etc. and these are coded and linked to each other. Fig 6 shows the tact schedule input task.

Reporting daily job by sub-contractors

The system provides daily job reporting function, which is previously done by manual (Fig 7). The information about the attended workers on a day is automatically migrated from the barcode reader (illustrated in Fig 5) to S-SMART. The supervisors of sub-contractors' then record the MU (the detailed location of work) and tact activity of the attended workers using preset menu in S-SMART.

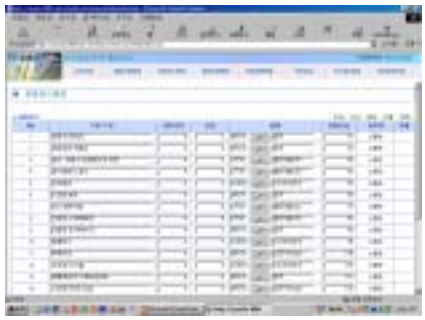

Fig 6. Establishing tact schedule

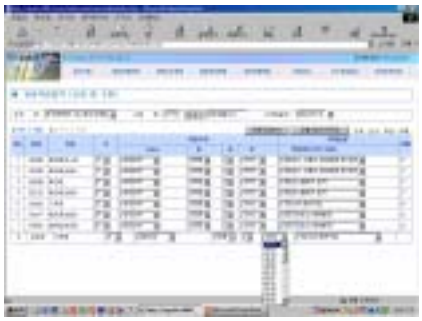

Fig 7. Reporting daily job by sub-contractors

Reporting the activity completion

The completed tact activity in a MU can be easily reported by checking the menu in S-SMART (Fig 8). The X-axis represents MUs and the Y-axis represents tact activities. When reported as completed activity by sub-contractors, the activity will be confirmed or rejected by main-contractor. The rejected activities will be marked in different color.

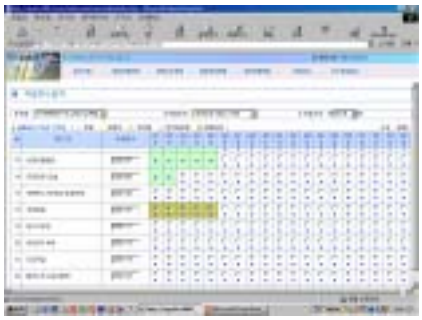

Fig 8. Reporting the activity completion

Monitoring the work progress

As shown in Fig 9, the work progresses can be clearly displayed for easy monitoring. The X-axis represents MUs and the Y-axis represents tact activities of a selected building block. At one glance, the progress can be captured. The number in the cells represents various information, e.g., input labor, finish date, start date, etc. The different color of the cells indicates that some of them are completed at first time and some others are completed by rework process. With this function, the overall status of work progress can be easily understood.

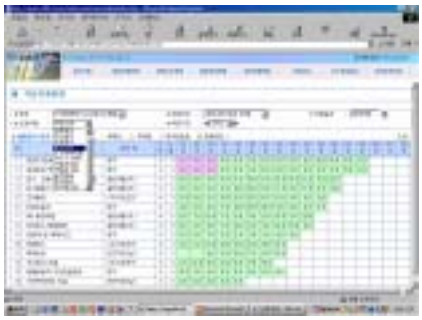

Fig 9. Monitoring the work progress

Monitoring the work flow with indicators

The work flow indicators, which are explained in section 4.1 are easily monitored by using S-SMART. The indicators can be analyzed against sub-contractors or MUs. This analysis is, as explained in Fig 4, to control the work flow. Fig 10 is showing the worker loyalty of the workers of a sub-contractor.

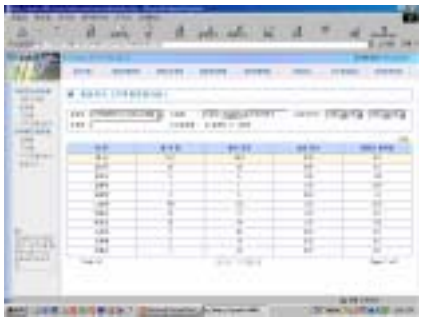

Fig 10. Monitoring the work flow with the indicators

5. CONCLUSION

Work flow is an important concept in lean construction, and its impacts on the effectiveness of construction process are well known. This paper viewed the tact or the rhythm of work flow as an important factor for managing continuous and repetitive works and proposed the tact scheduling method, the work flow indicators, and work flow monitoring system.

Firstly, a tact scheduling method —a planning method focused on the continuous work flow— is introduced. This method is believed to help reduce the duration consumed for conducting repetitive works by reducing the possibility of deviations from the planned work flow. By applying this method, the duration of finishing works of the case project was scheduled for 8 month, which is much shorter than previous Korean practices (see Table 1). This schedule was challenging but kept after all, and therefore, it can be concluded that the tact scheduling method is effective to manage the work flow of repetitive works and eventually to shorten the duration of repetitive works like finishing works of a building construction.

Secondly, a few indicators that measure the factors affecting the continuous work flow are suggested and validated. The logical concept of the indicators was validated through the intensive reviews by experts and the relationship among the indicators is statistically verified. Therefore, it can be concluded that the indicators proposed in this research are useful in monitoring the work flow of repetitive works scheduled by tact scheduling method.

Finally, this research presented the work flow monitoring system named S-SMART. This system is developed to support the overall process of tact schedule management and includes the followings as the major functions: establishing tact schedule, reporting daily job by sub-contractors, reporting the activity completion by sub-contractors, monitoring the work progress, and monitoring the work flow with the indicators. From the implementation of this system on the case project, it was found that the sub-contractors' involvement in the system use is quite challenging, however, the functions and performance of the system are satisfactory for supporting the process of the tact schedule management.

Acknowledgments

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SUPPLY CHAIN MANAGEMENT SYSTEM FOR CONSTRUCTION MATERIAL PLANNING

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Abstract: This study relies on integrated inventory theory which merges with the supply chain concept and aims at the steel bar material of precast factory's two-echelon supply chain system. In order to consider the variable demand rate, unfixed supply time, unfixed supply frequency and unfixed supply quantity, this study builds a strategic model that minimizes the total inventory cost of all participators. Based on the established model, the material's supply plan comes into existence, which takes into consideration the time and quantity of material supply, and the starting time of the supplier's production. It is expected that the study result can be useful reference for participators to deal with the material supply in a more efficient way.

Keywords: supply chain, integrated inventory, precast, material planning

1. INTRODUCTION

With characteristics of construction industry such as high construction cost, long duration, and complicated participators, it is very difficult to plan and deal with the managerial affairs in a construction project. As to materials, which consist large portion of construction cost, thus have the same problem. Without a complete plan, it may cause many obstacles in the supply procedure, for example delays in the schedule or wastes of other resources when some materials are supplied too late. And when some materials are supplied too early, it will also probably raise the inventory cost on carry, storage, overdue and insurance. In the construction industry, the planning and management of material supply are usually handled roughly with past experience and limited information. It lacks for some more systematic methods to increase the decision benefit.

However, in the other industries, many inventory theories have been well developed and matured to avoid supplying materials inappropriately. Some of these theories have already integrated the concept of supply chain management. In the opinion, all participators striding across boundaries in the transaction have been considered as a whole chain system. Instead of the individual optimum, the entirety optimum is the basis of policy making.

The traditional inventory model is based on the optimization for individual enterprise system. Relatively, by mutually coordinating and adjusting working processes to improve global benefits, the integrated inventory decision-making is focused on all partners of supply chain from upstream to downstream to minimize the total inventory cost.
From the theoretical development, Monahan (1984) fist proposed an economic order quantity model to take a lot-to-lot procuring strategy. The quantity discount pricing model will increase vender's profits. Lee and Rosenblatt and Banerjee（1986）expended and promoted Monhahan's model to enhance the vendee's order quantity by optimal discount pricing strategy. Further, Goyal（1988）, Srinivasan (1992) , Aderohunmu et al（1995）has proposed near idea and deeper description to improve the effectiveness of inventory management and reduce cost by business mutual corporation and pre-defined coordination. Obviously, the strategic alliance of specific supply chain will be highly relied on a rational mechanism which will benefit all the partnering members.

The integrated inventory model of this study is mainly developed for the precast factory and upper supplier of steel bar to be possible to make a globally beneficial supply planning. Therefore, this preliminary study is limited under the condition as

follows :

- pure inventory system (not including producing and distributing system)
- simple two hierarchy system
- many buyer to single supplier type
- decision making by minimum total cost
- single material consideration of steel bar
- variable material demand rate
- flexible supply times and quantities in certain period
- not allowable for material deficiency

2. ESTABLISHMENT OF THE MODEL

In the supply planning of integrated inventory model, the difference quantity between buyer's demand and supply can be regarded as the buyer's inventory level. Relatively, the same designation also fits the supplier side. By checking the inventory level of both sides and coping with individual cost requirements, the integrated inventory cost can be calculated. The objective function of this model lies on the total inventory cost combination of all supply chain participants. For purpose of simplicity, an illustration of developing the model is depicted as Figure 1 in which the specific buyer *m* is assigned to need three times of material supply in a certain time period. equations. The relative symbols used in this Figure can be referred at the end of this paper Notation.

2.1 Inventory cost for buyers

This present model considers only the item of inventory keeping cost for buyers, not including the other costs such as ordering, delivering and shortage cost. The inventory cost for buyers can be derived as following steps from equation (1) to (8).

Step 1. The demand area for buyer *m* at cycle *i:*

$$AreaD_{m,i} = Area1 + Area2 + Area3 \qquad (1)$$

where

$$AreaD_{mi} = \sum_{k=1}^{E_{mi,k}} \frac{1}{2} \left\{ 2\left[\sum_{s=1}^{k} \left(DCP_{mi,s} - DCP_{mi,s-1}\right) DR_{mi,s-1} \right] + \left(DCP_{mi,k+1} - DCP_{mi,k}\right) \left(DCP_{mi,k+1} - DCP_{mi,k}\right) DR_{mi,k} \right\} \cdot \left(DCP_{mi,k+1} - DCP_{mi,k}\right)$$

$$If\ k = E_{mi,k}\ ,Then DCP_{mi,k+1} = CSP_{i+1};$$

$$ps.\ DCP_{mi,0} = DR_{mi,0} = 0 \qquad (2)$$

Step 2. The supply area fro buyer *m* at cycle *i*:

$$AreaS_{mi} = SQ_{m,i,1} \cdot \left(SP_{m,i,2} - SP_{m,i,1}\right) + \left(SQ_{m,i,1} + SQ_{m,i,2}\right) \cdot \left(SP_{m,i,3} - SP_{m,i,2}\right) + \left(SQ_{m,i,1} + SQ_{m,i,2} + SQ_{m,i,3}\right) \cdot \left(CSP_{i+1} - SP_{m,i,3}\right) \qquad (3)$$

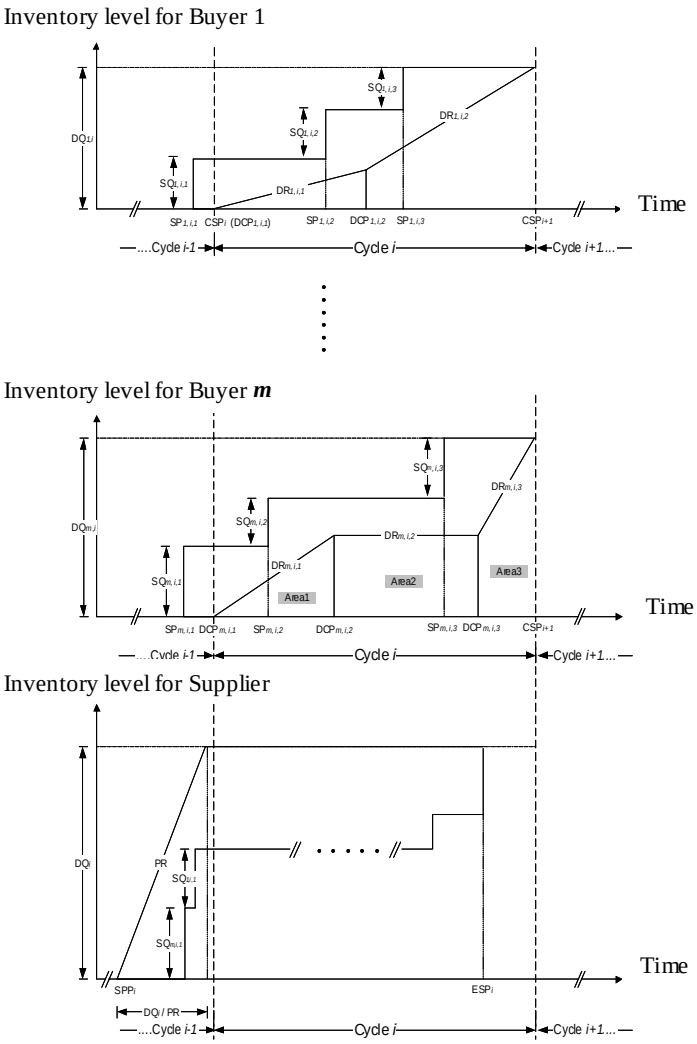

Figure 1. Expression of inventory level for the buyers and supplier

where

$$AreaS_{m,i} = \sum_{j=1}^{E_{m,i,j}} \left[\left(\sum_{s=1}^{j} SQ_{m,i,s} \right) \cdot \left(SP_{m,i,j+1} - SP_{m,i,j} \right) \right]$$

$$If \quad j = E_{m,i,j} \ , \ Then \ \ SP_{m,i,j+1} = CSP_{i+1} \qquad (4)$$

Step 3. The inventory area for buyer *m* at cycle *i* is shown in Figure1with bold lines circled:

$$AreaI_{m,i} = AreaS_{m,i} - AreaD_{m,i} \qquad (5)$$

Step 4. The keeping cost for buyer *m* at cycle *i:*

$$IC_{vm,i} = AreaI_{m,i} \times IUC_{vm} \qquad (6)$$

Step 5.The total cost for buyer m is the summation of all keeping cost at every cycles:

$$TC_{vm} = \sum_{i=1}^{E_i} IC_{vm,i} = \left\{ \begin{array}{l} \sum_{i=1}^{E_i} \sum_{j=1}^{E_{m,i,j}} \left[\left(\sum_{s=1}^{j} SQ_{m,i,s} \right) \cdot \left(SP_{m,i,j+1} - SP_{m,i,j} \right) \right] - \\ \sum_{i=1}^{E_i} \sum_{k=1}^{E_{m,i,k}} \frac{1}{2} \left\{ 2 \left[\sum_{s=1}^{k} \left(DCP_{m,i,s} - DCP_{m,i,s-1} \right) DR_{m,i,s-1} \right] + \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) \right\} \cdot \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) \\ \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) DR_{m,i,k} \end{array} \right\} \cdot IUC_{vm}$$

$$\begin{array}{l} If \;\; k = E_{m,i,k} \;\; , \; Then \;\; DCP_{m,i,k+1} = CSP_{i+1} ; \\ If \;\; j = E_{m,i,j} \;\; , \; Then \;\; SP_{m,i,j+1} = CSP_{i+1} ; \\ ps. \;\; DCP_{m,i,0} = DR_{m,j,0} = 0 \end{array} \tag{7}$$

Step 6. All buyers inventory cost can be equated:

$$TC_v = \sum_{m=1}^{E_v} TC_{vm} = \sum_{m=1}^{E_v} \left\{ \begin{array}{l} \sum_{i=1}^{E_i} \sum_{j=1}^{E_{m,i,j}} \left[\left(\sum_{s=1}^{j} SQ_{m,i,s} \right) \cdot \left(SP_{m,i,j+1} - SP_{m,i,j} \right) \right] - \\ \sum_{i=1}^{E_i} \sum_{k=1}^{E_{m,i,k}} \frac{1}{2} \left\{ 2 \left[\sum_{s=1}^{k} \left(DCP_{m,i,s} - DCP_{m,i,s-1} \right) DR_{m,i,s-1} \right] + \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) \right\} \cdot \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) \\ \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) DR_{m,i,k} \end{array} \right\} \cdot IUC_{vm}$$

$$\begin{array}{l} If \;\; k = E_{m,i,k} \;\; , \; Then \;\; DCP_{m,i,k+1} = CSP_{i+1} ; \\ If \;\; j = E_{m,i,j} \;\; , \; Then \;\; SP_{m,i,j+1} = CSP_{i+1} ; \\ ps. \;\; DCP_{m,i,0} = DR_{m,j,0} = 0 ; \end{array} \tag{8}$$

2.2 Inventory cost for supplier

Similarly, the total inventory cost for supplier is equal to the all keeping cost in every cycle. It is described by the following detailed steps.

Step 1. The producing area for supplier at cycle i:

Also, in Figure 1 the trapezoid area circled by producing lines can be calculated as

$$AreaP_i = \frac{1}{2} \left[\left(ESP_i - SPP_i - \frac{\sum_{m=1}^{E_v} DQ_{m,i}}{PR} \right) + \left(ESP_i - SPP_i \right) \right] \cdot \sum_{m=1}^{E_v} DQ_{m,i} \tag{9}$$

(10)

Step 2. Supplier's Supplement area at cycle i is the summation of all provision to buyers（*AreaSm,i*）

$$AreaS_{s,i} = \sum_{m=1}^{E_v} AreaS_{m,i} \tag{10}$$

Step 3. The inventory area for supplier at cycle i is circled by bold lines in Figure1:

$$AreaI_{s,i} = AreaP_i - AreaS_{s,i} \tag{11}$$

Step 4. The inventory keeping cost for supplier at cycle i :

$$IC_{si} = AreaI_{s,i} \times IUC_s \tag{12}$$

Step 5. The total inventory cost for supplier:

$$TC_s = \sum_{i=1}^{E_i} IC_{si} = \sum_{i=1}^{E_i} \left\{ \begin{array}{l} \frac{1}{2} \left[\left(ESP_i - SPP_i - \frac{\sum_{m=1}^{E_v} DQ_{m,i}}{PR} \right) + \left(ESP_i - SPP_i \right) \right] \cdot \sum_{m=1}^{E_v} DQ_{m,i} - \\ \sum_{m=1}^{E_v} \sum_{j=1}^{E_{m,i,j}} \left[\left(\sum_{s=1}^{j} SQ_{m,i,s} \right) \cdot \left(SP_{m,i,j+1} - SP_{m,i,j} \right) \right] \end{array} \right\} \cdot IUC_s$$

$$If \;\; j = E_{m,i,j} \; , \; Then \; SP_{m,i,j+1} = CSP_{i+1} ; \tag{13}$$

2.3 Joint total inventory cost

According to equation (8) and (13), the joint inventory cost cab be derived as following:

$$JTC = TC_v + TC_s = \sum_{m=1}^{E_v} \left\{ \begin{array}{l} \sum_{i=1}^{E_i} \sum_{j=1}^{E_{m,i,j}} \left[\left(\sum_{s=1}^{j} SQ_{m,i,s} \right) \cdot \left(SP_{m,i,j+1} - SP_{m,i,j} \right) \right] - \\ \sum_{i=1}^{E_i} \sum_{k=1}^{E_{m,i,k}} \frac{1}{2} \left\{ 2 \left[\sum_{s=1}^{k} \left(DCP_{m,i,s} - DCP_{m,i,s-1} \right) DR_{m,i,s-1} \right] + \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) \right\} \cdot \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) \\ \left(DCP_{m,i,k+1} - DCP_{m,i,k} \right) DR_{m,i,k} \end{array} \right\} \cdot IUC_{vm} +$$

$$\sum_{i=1}^{E_i} \left\{ \begin{array}{l} \frac{1}{2} \left[\left(ESP_i - SPP_i - \frac{\sum_{m=1}^{E_v} DQ_{m,i}}{PR} \right) + \left(ESP_i - SPP_i \right) \right] \cdot \sum_{m=1}^{E_v} DQ_{m,i} - \\ \sum_{m=1}^{E_v} \sum_{j=1}^{E_{m,i,j}} \left[\left(\sum_{s=1}^{j} SQ_{m,i,s} \right) \cdot \left(SP_{m,i,j+1} - SP_{m,i,j} \right) \right] \end{array} \right\} \cdot IUC_s$$

$$\begin{array}{l} If \;\; k = E_{m,i,k} \;\; , \; Then \; DCP_{m,i,k+1} = CSP_{i+1} ; \\ If \;\; j = E_{m,i,j} \;\; , \; Then \; SP_{m,i,j+1} = CSP_{i+1} ; \\ ps. \; DCP_{m,i,0} = DR_{m,i,0} = 0 \end{array} \tag{14}$$

2.4 Constraints for integrated inventory model

Based on the above model foundation, there are several constraints raised to make it possible for practical application.

- Supply time need to start before the required duration of demand
- There is a constraint of total supply numbers at a cycle
- There is a quantitative limit for a single supply.
- The cumulative demand quantity for buyers is not greater than total supply at any time.
- Total supply quantity for the supplier is always less than the cumulative producing quantity at

any time.

3 ILLUSTRATIVE EXAMPLE

To demonstrate the effects of the proposed model and corresponding supply plan, an illustrative example is presented in this section and the sensibility test is conducted as well. In this example of Figure 2, with three major participators, a steel bar supplier provides all demands on steel of a precast factory and Buyer B. And all conditional parameters needed in the model are assigned and shown in Table 1.

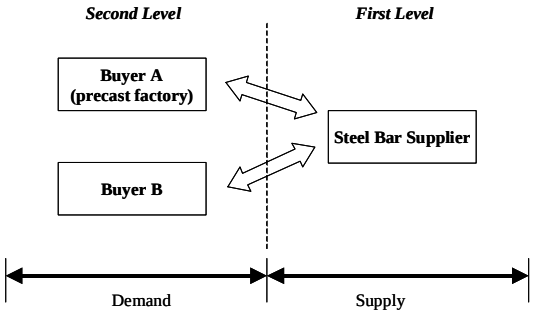

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Figure 2. Illustrative example for a two-echelon supply chain system

Table1. Conditional setting of the example

Common Conditions	Planning material target	D13 Steel bar	
	Planning period range	12 Weeks	
	Period length	2 Weeks	
	No. of period cycle	6	
	Supply time unit	2 Days	
Buyers Condition Setting		Buye A（precast factory）	Buyer B
	Inventory cost (dollar/ton/day)	15	12
	Unit of supply quantity（ton）	10	50
	Minimal supply unit per time	2	8
	Maximal supply unit per time	6	12
	No. of minimal supply per cycle	1	1
	No. of maximal supply per cycle	4	4
	Precedent time before the first supply (day)	1	1
Supplier Conditions	Inventory cost (dollar/ton/day)	10	
	Producing rate（ton/day）	350	
	Minimal precedent time before producing（day）	1	
	Maximal precedent time before producing（day）	2	

3.1 Calculation results

The following Table 2. and Table 3. indicates the distribution of inventory costs allocated at each participator of this example setting and the joint costs under the consideration of minimizing the overall inventory cost, which is the outcome of the integrated inventory model suggested by this research. Figure 3 further shows the prominent effect of the model that all overall costs considering individual minimization are much higher than that of the present model.

Table 2. Comparison of inventory cost among participators

Period cycle	Buyer A		Buyer B		Steel Bar Supplier		Joint Cost（$）
	cost（$）	Percentage on cycle total cost (%)	cost（$）	Percentage on cycle total cost (%)	cost（$）	Percentage on cycle total cost (%)	
1	4725	2.72	51600	29.74	117200	67.54	**173525**
2	2175	2.38	43800	47.99	45300	49.63	**91275**
3	4800	3.18	48000	31.79	98200	65.03	**151000**
4	2250	2.94	37200	48.60	37100	48.47	**76550**
5	4650	3.03	54600	35.63	94000	61.34	**153250**
6	5925	5.71	31200	30.08	66600	64.21	**103725**
sum	24525	3.27	266400	35.55	458400	61.18	***749325***

Table 3. Comparison of total joint inventory cost

Cycle	Total joint cost conducted by the present model（$）	Total joint cost led by buyer A（$）	Total joint cost led by buyer B（$）	Total joint cost led by steel bar supplier（$）
1	173525	220525	210125	193525
2	91275	116275	112175	97175
3	151000	196600	189200	166800
4	76550	101150	99150	80950
5	153250	190450	183750	171350
6	103725	147925	145025	112025
sum	***749325***	***972925***	***939425***	***821825***
Increasing cost percentage compared with the present model (%)		***29.84***	***25.37***	***9.68***

4. SENSITIVITY ANALYSIS

To verify the effect of applying integrated inventory model, several sensitivity tests depending on the variable producing rate of steel bar towards three major model participators are conducted. All testing results reflect the expected inference. Figure 4 further indicates that the cost of steel bar supplier has the highest sensitivity toward the variable producing rate than other participators, but there is not a linear relation between the supply rate and the overall cost. In other words, there exist a supply rate that can also minimize the overall inventory cost.

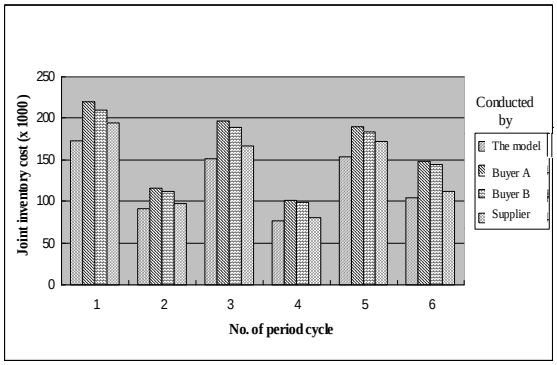

Figure 3. Comparison of total joint inventory cost conducted by different participators

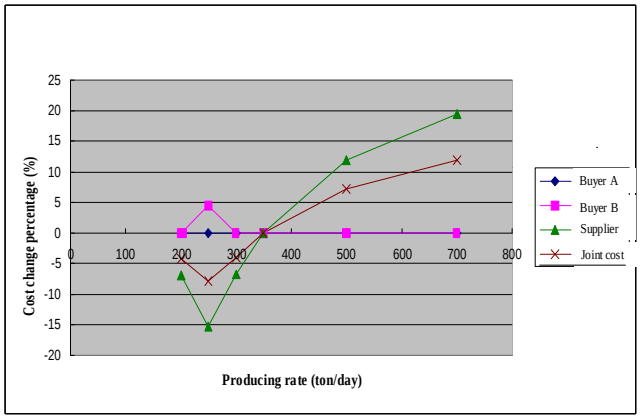

Figure 4. Sensitivity analysis of variable producing rate in the illustrative example

5. CONCLUSIONS

In accordance of the theorem of supply chain that optimizes the whole profits of all participators, this research provides a two-echelon integrated inventory model for steel bar supplier and precast factories with the variable demand rate, unfixed supply time, frequency and quantity. The illustrative example also demonstrates the effectiveness of the model. With the satisfactory outcomes for each case in the example and the result of sensitivity analyses, we can conclude as follows:

1. The present integrated inventory model minimizes the overall inventory cost compared with any inventory models considering individual minimization.

In the example, the overall inventory costs considering any individual minimization are higher than that of integrated inventory model (Minimizing the cost of individual precast factory has a 29.84% higher than the present model of overall integrated viewpoint, while buyer B with 25.37% higher and the steel bar supplier with 9.68% higher) It can be concluded that planning with the cost minimization only for one participator could induce a peak of cost for another, however, which results in a higher overall inventory cost. Although the integrated inventory model cannot guarantee a lowest cost for each participator, its overall cost can rationally reach a minimum. This conclusion complies with the essence of supply chain theorem.

2. Planning centered at the participator with lowest impact on material cost would induce the highest overall inventory cost

According to the figures shown in the example, the inventory cost of the precast factory is much lower than that of Supplier A, and planning centered at the precast factory induce the highest overall inventory cost. The similar result can also be observed in the sensibility test.

3. Planning with higher supply frequency but lower quantity would possibly reduce the overall inventory cost

According to the result of the sensibility test, with the assumption that suppliers can fully meets the demand of the precast factory, planning with higher supply frequency but lower quantity would reduce the overall inventory cost. In other words, a higher supply frequency avoids high holding cost, and thus reduces the overall cost. This reflects the concept of Just In Time inventory management (JIT) discussed and applied in many industries around the world recently. A high supply frequency, however, may also induce other cost, such as production cost, transportation cost, and inspection costs, which results in the increase of the overall cost. Therefore, a more complete inventory model covering the quantity-frequency tradeoff is necessary to take to confirm the minimum of overall cost.

4. There indeed exists a supply rate that minimizes the overall inventory cost

According to the result of the sensibility test, there is not a linear relation between the supply rate and the overall cost. If the supply rate is set as 250 tons per day in the same case (350 tons per day is the default), it turns out a lower overall inventory cost. As a result, there exist a supply rate that can also minimize the overall inventory cost, which can be obtained by applying interpolation in the sensitivity test.

6. FUTURE RECOMMENDATIONS

Due to the real complexity and characteristics of construction industry, it really requires to take many factors into account when enterprises make their material resource planning beyond the study. That is,

the scope of consideration would definitely need to enlarge in applying the theorem of supply chain in such plans. This research could be a pilot study of designing a supply chain for the construction industry in Taiwan and thus many improvements of the model and other methodologies used for optimization are necessary to induce. First, the major contradiction of theorem of supply chain lies on the reallocation of the cost saved by the integrated consideration for all participators as a team. The distribution of profits needs to be addressed in the entire planning system according each role and its contribution to the chain. Secondly, time points for billing and parameters such as other cost accounts, the level of inventory, and discount due to lot size, should be included into the inventory model in order to enhance the precision of the prediction. Finally, more effective methodologies to find the optimal solution such as Generic Algorithm (GA) or Neural Network (NN) can be introduced to solve the problem of combination explosion in the real world.

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Notation

i = planning cycle index
j = supply index in a cycle
k = demand index
m = buyer index
SQ =Supply Quantity
SP =Supply Time Point
Ei = the last cycle index for joint planning cycle
Ev = buyer's ordering quantity
Em,i,j = the index for buyer m at cycle i
Em,i,k = the last index for buyer m at cycle i to change demand
CTL =Cycle Time Length
CSP = Cycle Start Point
DR = Demand Rate
DCPm,i,k = Demand Change Point
DQ =Demand Quantity
SPP =Start Produce Point
ESPi = End Supply Point
PR = Produce Rate
IUCvm = Inventory Unit Cost for buyer m
IUCs = Inventory Unit Cost for supplier
ICvm,i = Inventory Cost for buyer m at cycle i
ICsi = Inventory Cost for supplier at cycle i
TCvm =Total Cost for buyer m
TCs = Total Cost for supplier s
JTC = Joint Total Cost

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APPROACH TO MULTI-OBJECTIVE EVOLUTIONARY COMPITATION METHOD FOR GENERATING VARIABLE WALKING PATTERNS

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Abstract: The generation of the optimal walking trajectory is an important question for a biped robot to keep walking stably. This paper is proposed for generating the walking trajectories resulted in best performance of the biped robot using multi-objective evolutionary computation. We formulate a trajectory generation problem as a multi-objective optimal problem. We obtain all Pareto-optimal solutions on the feasible solution region for various walking pattern generation of a biped robot in simulation.

Keywords: Multi objective, evolutionary computation, Pareto optimal, walking pattern, ZMP

1. INTRODUCTION

In recent years, there are many studies about the biped type robot, because the biped robot is more adaptable than the mobile robot in a varied environment. And this type can have more diverse possibilities in planning the motion. In addition, it can walk over some obstacles, so that there is no need to go a long way round. Above all it is more human-friendly than any other types. But it has also many weak points. It is easy to fall down. So, it is difficult to control the walking without falling down, we should consider the stability of biped locomotion in various terrain. Besides, the biped robot has high complexity and redundancy. So the generation of the optimal walking trajectory is an important problem for the biped robot to keep walking stably.

There are two schemes for the walking pattern generation. First, one is a scheme which a designer manually defines the parameters to generate the walking trajectory. [11] And the other is a scheme which a designer intelligently finds all parameters to satisfy the constraints required in walking. [1]- [10] While the former has to make extensive efforts of trials and errors to get the better performance, the latter does not need to repeat some efforts. So, the latter one is studied by many researchers.

In this paper, we want to have no efforts of trials and errors manually using the evolutionary Algorithm. And we want to find all possible solutions for the adaptability of this system. First we formulate the trajectory generation problem as the parameter search problem. So we confirm that our EA scheme is valid. In addition, we formulate this problem as the multi-objective optimal problem. And using multi-objective evolutionary computation, we can find all feasible trajectories, which satisfy stability condition dynamically, consume the minimum energy, and simultaneously move the robot faster. These objectives are considered simultaneously, although they are often competing. While previous evolutionary methods are applied to obtain the best solution for a specified fitness function, proposed method can find many obtained possibilities which can be applied flexibly for planning walking patterns fit for given environment. So, this paper is organized as follows. In Section 2, we describe the model of a biped robot and define the walking trajectory with the necessary parameters. Next, in Section 3, we propose the multi-objective evolutionary scheme for the walking trajectory generation. We define 4 fitness functions and apply the EA. We formulate this problem as multi-objective optimization problem. And we apply the strength Pareto-optimality improved for the walking trajectory generation. Next, we verify the proposed scheme by simulation in Section 4. Finally we conclude this paper in Section 5.

2. WALKING TRAJECTORY

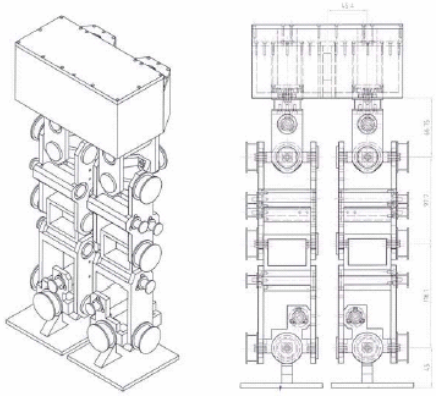

Figure 1. The biped robot

Figure 1 represents the 12DOF (degrees of freedom) biped robot. In order to easily approach the dynamics of this system, it is assumed that the robot link is a point mass. It is assumed that every parameter is known obviously. There are 3DOF in the hip joint, 1DOF in the knee joint, and 2DOF in the ankle joint. For a sagittal plane, the foot trajectory is the coordinate of the ankle position,. The hip trajectory is the coordinate of the hip position.

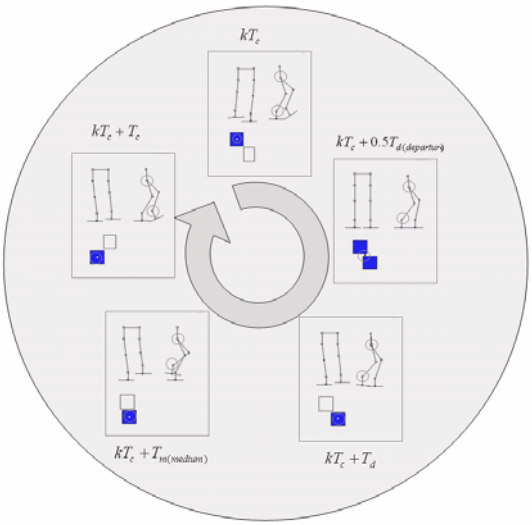

Figure 2. Walking cycle

Figure 2 describes the configurations of the biped robot in via point at time t. [11] If we select the proper parameters, which are the stride, the maximum height position of the swing foot ankle, the inclination rate of the robot side and front, and the max-min height positions of the hip, we can make a continuous trajectory for a one step of the biped robot using the interpolation technique. And we design the desired ZMP trajectory to be assured the stability of the dynamic walking. So, the total numbers of the unknown parameters are 12. In order to find the optimal trajectory, we should formulate this problem as the search problem at the variable constrained situations.

3. MULTI-OBJECTIVE EVOLUTIONARY COMPUTATION FOR TRAJECTORY PARAMETERS

In this section, we formulate the trajectory parameter problem as multi-objective optimization problem. And we propose the 4 fitness functions for three objects. First, evolutionary computation is a search algorithm known to be robust for optimization problem. This method is based on the natural selection and population genetics. So, it is based on the interaction and biological evolution between individuals and the natural environment. The survival of the fittest exists. It is very adaptable in environment. Nature produces a population with individuals that are better fit to the environment from a random population. Using this algorithm, we want to find the best parameters for all via points of walking trajectory.

3.1 PARETO-OPTIMALITY

In applications of optimization methods, the solution of such problems is usually computed by the weighted sum of the objectives. The multi-objective optimization problem finds the point $x = (x_1, \ldots, x_n)$ which optimizes the values of a set of objective functions $f = (f_1, \ldots, f_m)$ within the feasible region of x (Figure 3). Figure 3 describes the set of the Pareto optimality solutions of the minimization problem. In detail, the definition of the Pareto-optimality is as follows: Assume a minimization problem and think about two arbitrary vectors $a, b \in P$ It can be said that a dominate b.

$$f_i(a) \le f_i(b), \forall i = 1, \cdots, m, \wedge$$
$$f_i(a) < f_i(b), \exists i = 1, \cdots, m. \tag{1}$$

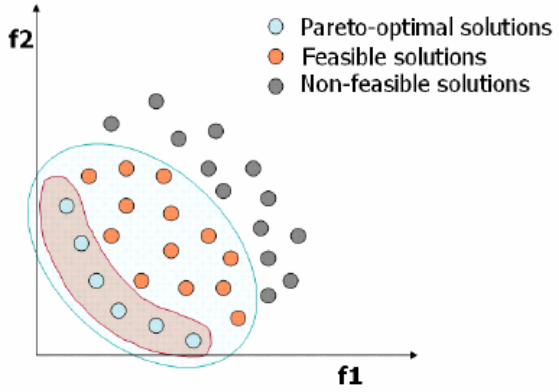

Figure 3. Pareto-optimal solutions

Every vector which is not dominated by any other vector is called non-dominated set or Pareto-optimal set. For the walking trajectory, we can define that a set of objective functions are f = (fstability, fenergy, fmobility). fpenalty should be considered, because, if fpenalty(x) ≠ 0, this vector x is not feasible and finally cannot be a solution. In multi-objective problem, there are many schemes to find the non-dominated set of solutions. Among the others, the strength Pareto evolutionary algorithm which is modified for the walking trajectory problem is used. In other conventional ways, there is a serious problem that the solutions to be sought out are centralized in a specified part. So to resolve such a difficulty, many related works are carried out. As a result, some methods considering such a difficult point is very useful. The strength Pareto evolutionary algorithm is one of them.

3.2 THE PROPOSED ALGORITHM USING THE MULTI OBJECITVE EVOLUTIONARY COMPUTATION

The proposed algorithm used to solve this multi-objective optimization problem is in brief as follows:

(1) Initialize the populations P (vectors) and create the empty array for non-dominated set NP (Non-dominated vectors).
(2) Find the non-dominated members in P. However, to decide whether a vector is the member of the non-dominated set, $f = (f_{stability}, f_{energy}, f_{mobility})$ of the vector cannot be applied. Because, if the position of a vector x at every time is violate the penalty condition, $f_{stability}$ and f_{energy} may be equal to zero. So although they cannot be the solution to satisfy feasible constraints, they can pretend to be a member of the non-dominant solutions. So each vector should be translated as much as its penalty fitness value in objective space. So the feasible region is filtered by removing impurities (Figure 4). And then find the non-dominated members in P. Transfer them from P to NP.
(3) Leave the non-dominated members in NP, and remove the dominated members in P.
(4) If the numbers of the non-dominated solutions are more than the desired number Nnondom, remove needless solutions in NP by clustering method.
(5) Evaluate the fitness of all vectors in P and NP.
(6) Select vectors in P and NP using genetic operations such as crossover, mutation, and tournament with replacement.
(7) If the numbers of the generation is equal to maximum generation, terminate this algorithm; else go to (2).

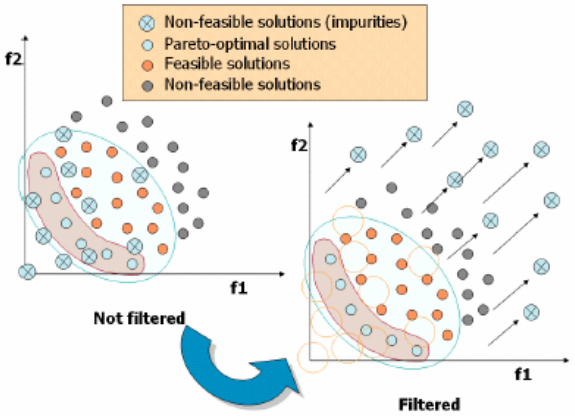

Figure 4. Filtering of the feasible solution space

3.3 DEFINITION OF GENES

Vectors consist of parameters to want to find out. As stated above, a vector means a set of the known parameters. Because the numbers of unknown values are 12, search space is so wide that it may be troublesome to converge on the global solution. To reduce such an effort, genes have some constraints. These are as follow:

$$
\begin{aligned}
F_d: &\quad \left(\tfrac{F_f+F_b}{2}\right) \le F_d \le 2(F_f+F_b)\\
F_{mh}: &\quad F_a \le F_{mh} \le (F_a+L_1)\\
F_{ml}: &\quad \left(\tfrac{F_f+F_b}{2}\right) \le F_{ml} \le \left(\tfrac{3(F_f+F_b)}{2}\right)\\
f_b: &\quad 0 \le f_b \le \tfrac{\pi}{3}\\
f_f: &\quad 0 \le f_f \le \tfrac{\pi}{3}\\
H_{max}: &\quad (F_a+L_1) \le H_{max} \le (F_a+L_1+L_2+L_3)\\
H_{min}: &\quad (F_a+L_1) \le H_{min} \le H_{max}\\
d_{hf}: &\quad \left(\tfrac{F_f+F_b}{3}\right) \le d_{hf} \le (F_f+F_b)\\
d_{hb}: &\quad \left(\tfrac{F_f+F_b}{3}\right) \le d_{hb} \le (F_f+F_b)\\
\theta_{max}: &\quad 0 \le \theta_{max} \le \tfrac{\pi}{4}\\
\alpha: &\quad 0 \le \alpha \le 2\\
T_c: &\quad 5 \le T_c \le 15.0
\end{aligned}
$$

With these constraints, the reminders of the trajectory parameters are as follows:

$$T_d = \frac{x_f(T_d)}{2F_d} T_c$$

$$T_m = \frac{F_{ml}}{2F_d} T_c$$

Each parameter means as follows:

F_d : A stride
F_{mh} : z coordinate of the ankle in the highest position
F_{ml} : x coordinate of the ankle in the highest position
f_b : foot angle when the swing foot leaves
f_f : foot angle when the swing foot lands on the ground
H_{max} : maximum height of the hip
H_{min} : minimum height of the hip
d_{hf} : the distance between the front ankle and the hip
d_{hb} : the distance between the rear ankle and the hip
θ_{max} : maximum inclination of the robot body
α : a scale factor for the inclination of the robot body
T_c : a period

3.4 OPERATOR

We select the parents to produce the new offspring and population with the random tournament. There are 3 steps for this selection method. First randomly select two vectors in current population. And then compare the score of one vector with the other, and finally select the vector, who wins victory in a competition, as parents of the next generation. Prior to this procedure, the best individual is inherited to the next generation. After selection process come crossover and mutation process. To maintain the diversity of each generation, arithmetic crossover and uniform mutation is applied to this procedure.

3.5 THE PROPOSED FITNESS FUNCTIONS

Here we apply the fitness function to be appropriate for the biped robot. We consider stability property, energy efficient performance, mobility property, and penalty for the basic constraints during a cycle. Each factor is used to define the fitness function. Let $f_{stability}$ be the stability function for the fitness function. The definition of this function is shown below:

$$f_{stability}(\mathrm{x}) = \frac{f_{zmp}(\mathrm{x})}{\max_{\mathrm{y}\in\Psi} f_{zmp}(\mathrm{y})} + \frac{f_{shake}(\mathrm{x})}{\max_{\mathrm{y}\in\Psi} f_{shake}(\mathrm{y})} + \frac{f_{config}(\mathrm{x})}{\max_{\mathrm{y}\in\Psi} f_{config}(\mathrm{y})} + \frac{f_{hip}(\mathrm{x})}{\max_{\mathrm{y}\in\Psi} f_{hip}(\mathrm{y})} \tag{2}$$

where ϕ means a set of points in the current population. Each term denotes the normalized functions, which is as follows:

$$f_{zmp}(x) = \sum_{k=0}^{N}\left(\frac{\sqrt{(x_{zmp}-x_{dzmp})^2+(y_{zmp}-y_{dzmp})^2}}{N}\right) \tag{3}$$

$$f_{shake}(x) = \max(y_{zmp}) - \min(y_{zmp}) \quad (\text{if} \quad T_d \le t \le T_c) \tag{4}$$

$$f_{config}(x) = \frac{F_{mh}}{T_c F_d} \quad (\text{if} \quad \frac{F_{mh}}{F_d} > C_r) \tag{5}$$

$$f_{hip}(x) = \frac{H_{\max} - H_{\min}}{H_{\max} + H_{\min}} \tag{6}$$

The first term is a mean value of the error between the desired ZMP and actual ZMP for all sampling times. And the second term represents a degree to be shaken from side to side during a single support phase. And the next term is related to the configuration of foot trajectory. So the larger is this value, the higher is the risk that the motor may go to the utmost limit of velocity and torque, and then the stranger is the shape of foot trajectory. Finally, last term describes the motion of the hip. So if this value is lager, whole configuration of walking trajectory is very abnormal and the robot may stoop. So these terms should be minimized. All terms can have the relative weight rate so that the weighted ratio of each term can change results differently. We must consider these points.

And then let fenergy be the energy efficiency function. The definition of this function is shown as follow:

$$f_{energy}(x) = \sum_{k=0}^{N}\left(\frac{z_z(kT_s)}{N}\right) \tag{7}$$

, where the za is the z coordinate of the ankle of the swing leg. It means that the height of the swing leg from the ground is minimized. It can be applied for looking over the change of the joint angle slightly.

Next, let fmobility be the mobility performance function. The function can be derived as follow:

$$f_{mobility}(x) = \frac{10}{velocity} = 10\frac{T_c}{F_d} \tag{8}$$

It is shown that if the value of the mobility function is less, a mobility performance is better and the motion is faster. So, these three fitness functions which are mentioned above are objects for the multi-objective optimization.

At last, here, let penalty function for the constraints. Above all, penalty function has the highest priority, because, if a certain vector violates the penalty condition, we cannot evaluate the other functions. If vector x has singularity positions, there can be no solution of the inverse kinematics so that the other functions cannot be defined about such positions. If the position at every time is violating the penalty condition, fstability and fenergy may be equal to zero. So, it is as follows:

$$f_{penalty}(x) = \min\left(\sum_{k=0}^{N}\left(P(KT_s)\right), P_{MAX}\right) \tag{9}$$

, where $(P(KT_s))$ is a function to obtain a penalty value at each sampling time, P_{MAX} is the maximum values in relation to the total value fpenalty.

After all, we may be able to make the single object optimization problem by weighted summation of all fitness function. But we should tune weighted ratios so that we can obtain the best trajectory which has the desired performances. Because there is no chance that we cannot choose another solution, this work is very delicate. So, as previously stated, the walking trajectory problem should be regarded as multi-objective optimization problem. Because this problem is to simultaneously optimize several incommensurable and often competing objectives. We can have more chances that we may choose.

3.6 APPLIED PARETO-OPTIMALITY

To solve this multi objective optimization problem, we applied Strength Pareto algorithm [14] in the fitness assignment and clustering of non-dominant vector set. We add the penalty term to the fitness assignment terms in order to find the penalty-zero solutions.

4. SIMULATION

In this section, we will verify the proposed scheme for the walking trajectory generation of a biped robot by some simulation results. The proposed evolutionary scheme improved for the biped robot shows that several trajectories optimized for robot walking can be obtained by this method. And

importing multi-objective concept, we show that possible solutions of trajectory problem can be solved at a time.

The parameters used in the multi-objective optimization evolutionary computation simulation are listed in Table 1.

Table 1. Parameters of multi-objective evolutionary computation process

Parameters	*value*
Population size	200
Non-dominant vector size	50
No. of generation	200
Crossover ratio	0.3
mutation ratio	0.1
system parameter(b)	2

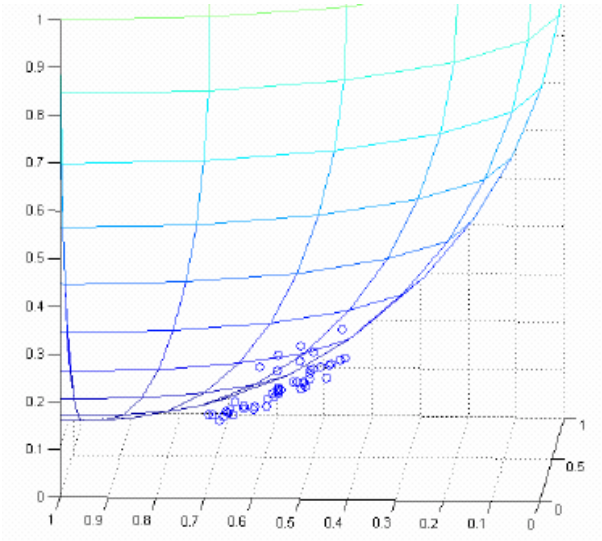

Figure 5. The Pareto-optimal solutions for this problem: Numbers of NP = 45

As you can see, Figure 5 shows that this method can enable to obtain various feasible solutions in at all. Every solution is different from each other. They are non-dominant vectors. Actually, we can search so many other feasible sets of trajectory parameters, as continuously repeating this multi-objective evolutionary computation process. Because they satisfy the Pareto-optimal condition each other, every solution has advantage that the fitness property is better than any other solutions in one objective at least. In EA, we need to iterate so many times this procedure for getting similar results with multi-objective evolutionary computation. As previously stated, we already obtain many solutions which have different features of walking trajectory. Now we investigate several cases for the walking patterns as follows (Table 2).

Table 2. Solutions of multi-objective evolutionary computation process

	Solutions		
	Case 1-1	Case 1-2	Case 1-3
vector[0]	123.011755	53.811797	82.587302
vector[1]	62.21682	56.034036	60.770987
vector[2]	134.275185	77.461114	82.866849
vector[3]	0.426906	0.487901	0.346573
vector[4]	0.911742	0.391433	0.771708
vector[5]	211.714223	214.965783	212.968968
vector[6]	208.69717	197.12557	206.377906
vector[7]	32.441752	32.951596	33.82173
vector[8]	60.752912	55.13491	66.071869
vector[9]	0.449804	0.51535	0.46066
vector[10]	0.747206	0.987681	0.840519
vector[11]	5.935924	5.264871	6.552376
stability	0.051932	0.228587	0.05523
mobility	0.414531	0.702854	0.549971
energy	0.348089	0.135315	0.258184

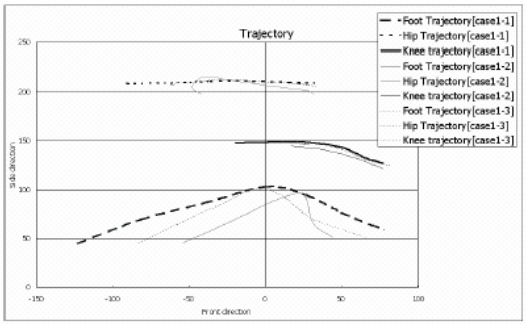

Figure 6. Examples of the walking patterns using the Pareto-optimal solutions

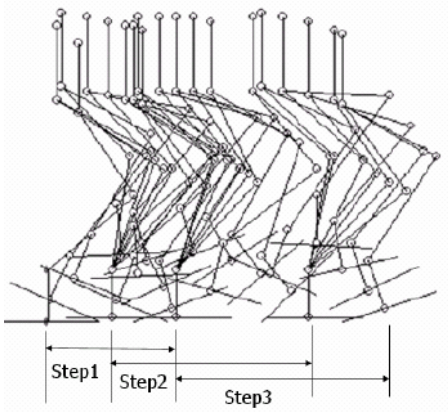

Figure 7. Simulator result of the walking patterns

Finally, we can generate some kind of walking patterns properly selecting the solutions mentioned above. Among them, Figure 7 describes three steps. Second step is different from the other steps in step length property. In this way, it is confirmed that there are many possibilities that we can obtain diverse walking patterns.

6. CONCLUSION

In this paper, EA is proposed to find the solution without the manual efforts mentioned above. We propose three objects. First, the one is about stability

of walking trajectory. And next is about efficiency of energy. Finally, the other is about the mobility of robot. EA, for a single objective optimal problem of walking trajectory generation, is applied to optimize the weighted sum of three normalized object values and one penalty function. So, by this processes, we can obtain a optimal solution for walking trajectory of biped robot. But this is not so good. Because these objects have a conflict each other, we cannot optimize at the same time. So we propose the multi-objective evolutionary computation algorithm to find many useful solutions all at once. And we can obtain the multiform patterns using these solutions for walking like human. To apply the multi-objective problem, we use the modified the strength Pareto-optimality algorithm for this situation. At last, in simulations, proposed algorithm to generate the walking trajectory is verified.

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Telerobotic Mini-Golf: Interactive Learning Performance of Human Teleoperators

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Abstract: A telerobotic test-bed has recently been built between KAIST(Korea) and Saga University(Japan). This paper presents its first research work on investigating the interactive learning performance of human teleoperators. For this purpose, the telerobotic test-bed was re-shaped to a telerobotic golf system. Eleven players were participated, and their interactive performance with the telerobot was carefully analyzed for the errors and skills that they demonstrated. It was observed that human teleoperators first try to avoid errors that they did in the previous trials, and then make efforts to explore new skills. It was also experienced that simple task oriented design features and their coordination could significantly improve telerobotic system performance without making it to an excessively sophisticated shape. Interactive learning with naked-eye vision was compared with that of camera vision, and an effective training procedure for human teleoperators was revealed. Some simple, yet appropriate techniques have also been identified that significantly enhance the performance of human teleoperators.

Keywords: Teleoperation, Interactive learning, Telerobotic mini-golf

1. INTRODUCTION

Telerobotics is becoming an increasingly important research and application area. Telerobotics and teleoperations have been introduced in a wide range of applications recently. Ranging from space and on-orbit [1], teleoperations have found its potential in undersea [2], medical [3], welfare [4], rescue [5], and entertainment [6] applications. The trend of telerobotics has been stimulated with its Internet-based implementation [7], [8]. The classical problems of telerobotics are:

(a) Instability caused by time delay
(b) Poor visual feedback (with 2D cameras)

Time delay instability has been thoroughly analyzed in [9], [10], and proposed the supervisory control that ensures stable teleoperation. For the visual feedback problem, virtual reality based techniques have been suggested [11], [12], [13]. Graphics-intensive systems generally consume a significant time for vision data processing. When object recognition [14] and modeling are required, such systems render additional errors to the operator interface, thereby, degrading effective operation.

Although efforts are taken to develop sophisticated systems, it seems that there has not been a thorough investigation to understand and describe how the human operator cognitively interact with the telerobot [15], and his learning and adaptation patterns. Such information might provide very important clues to develop telerobotic systems that are capable of exploiting teleoperator skills by way of properly coordinated, simple, yet appropriate techniques. This paper is aimed along this direction of research, where we are particularly interested in thoroughly observing the interactive learning performance of human teleoperators. The recently built telerobotic test-bed between KAIST(Korea) and Saga University(Japan) was re-shaped to a simple, yet challenging telerobotic golf system. Eleven players have been involved in playing the game producing valuable data and experience. By analyzing their interactive actions, and what they experienced, some key issues in telerobotics have been observed with more clarity. Teleoperation with naked-eye vision has been found to be an effective pre-training for teleoperators before they actually interact with camera vision. Simple, yet effective developments have also been identified.

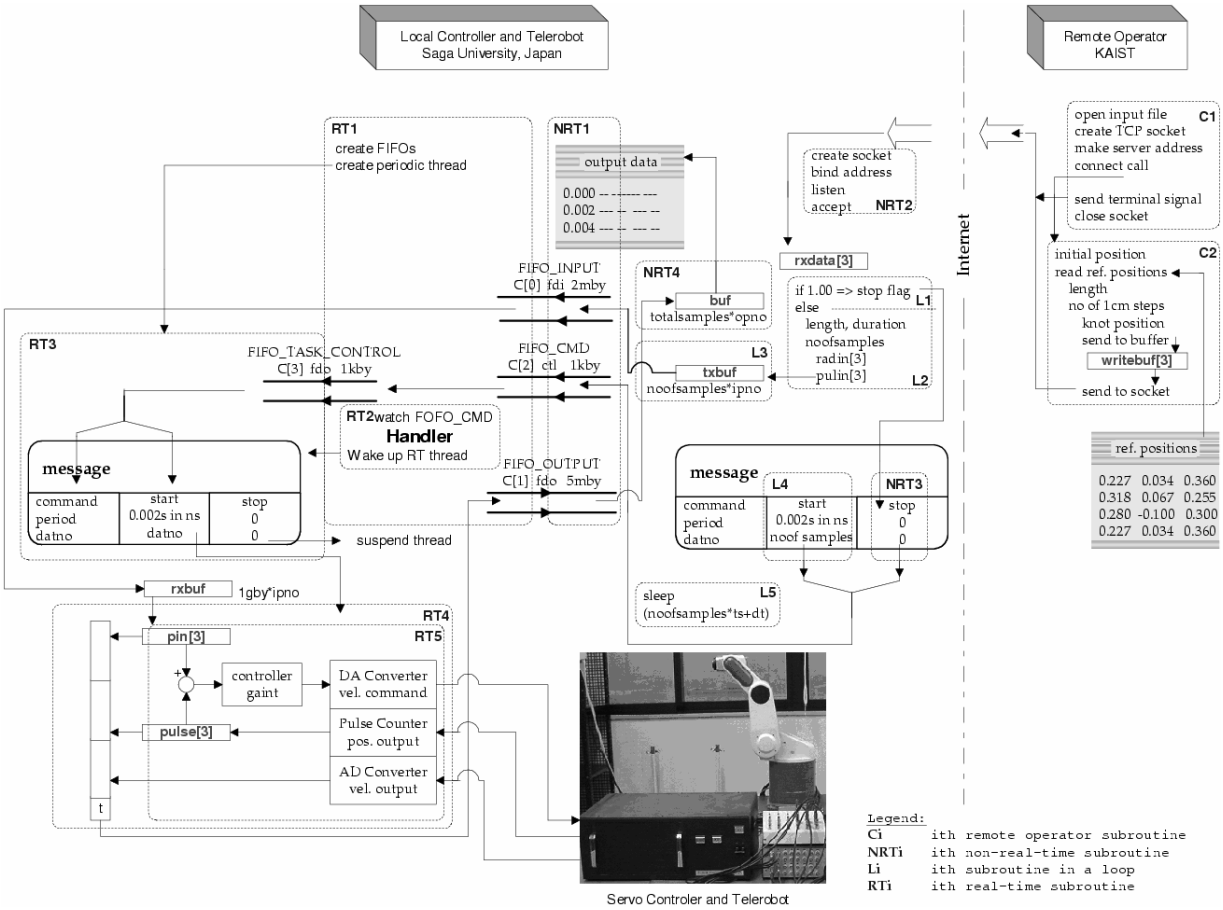


Fig.1 The design of the telerobotic system between KAIST(Korea) and Saga University(Japan)

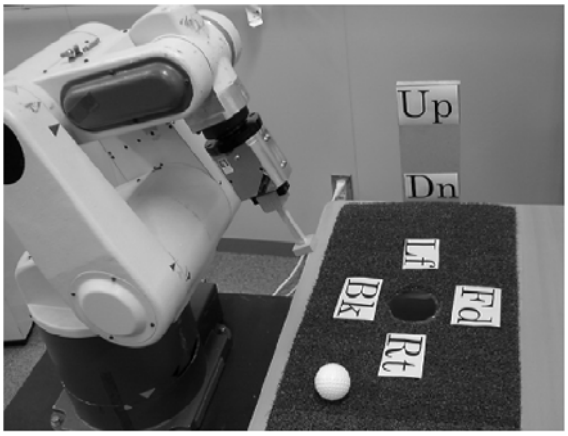
2. THE TELEROBOTIC TESTBED

2.1 Design Features

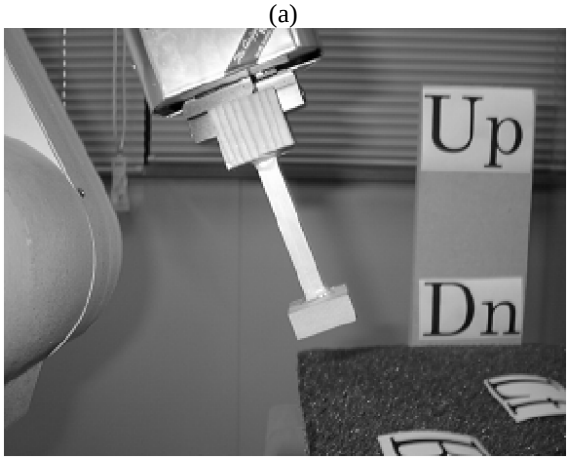
Figure 1 illustrates the recently built telerobotic test-bed between KAIST(Korea) and Saga University(Japan). The remote operator terminal resides in KAIST, and the local controller and telerobot reside in Saga University(Japan) as illustrated in Fig. 1. The two sides communicate through TCP sockets over the Internet. Remote operator terminal reads motion commands from a data file, or through the keyboard, and sends those commands to the local controller in Saga University (C1). The local controller runs a non real-time loop (L1-L4) within which it reads the incremental positions, and calculates distance between them, duration for the incremental motion, and number of input samples in each incremental motion (L1 and L2). The input data for the incremental motion of the telerobot is sent to a serial buffer and then placed onto FIFO_INPUT (L3). This incremental motion is planned assuming uniform end-effector speed. Then, the ``start" command is written onto the ``message" structure, together with the number of input data samples for the incremental motion (L4). The real-time control loop (RT4) executes the feedback control of the robot while reading motion data from the FIFO_INPUT. When there is no motion data in FIFO_INPUT (temporarily), then the RT5 control loop operates. RT5 uses the last position data and stabilizes the robot at that joint configuration until next incremental position data appears on FIFO_INPUT. However, RT5 does not write position output (which is unnecessary) to the FIFO_OUTPUT.

2.2 Task oriented System Design for Telerobotic Golf

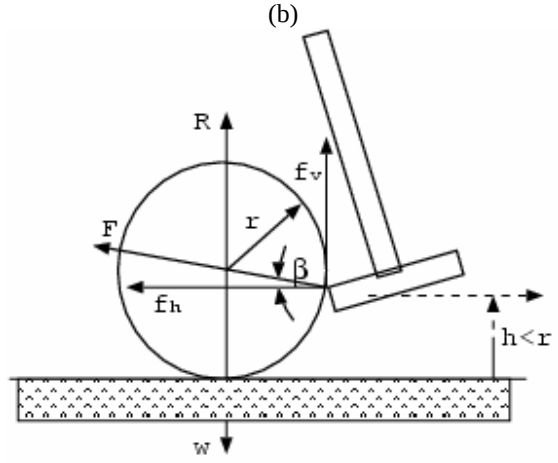
By way of task oriented design, the telerobotic test-bed was customized to a telerobotic golf system as shown in Fig. 2(a). The key design features are explained as follows:



(a)



(b)



(c)

Fig.2 Telerobotic golf: (a) The golf court, (b) Putter design, and (c) Force diagram of the putting stroke

Putter Design

The putter was designed as shown in Fig. 2(b), with a thin long handle terminating at 1[cm] thick, square shaped piece of wood. The handle is sufficiently thin so that it does not block the view of the ball and the hole during the play. The dimensions of the square shaped end are sizable so that its positioning is not required to be precise before putting the ball. The thickness of the tool is small enough so that it always contacts the ball close to the ground, thereby, avoiding unnecessary force on the ground. This feature also provides more rolling torque, which facilitates motion. Figure 2(c) shows the forces acting on the ball when it is in contact with the putter, which is held closer to the ground. The rolling torque $\tau = Fr\cos\beta$, where F is the contact force on the ball, r is the radius of the ball, and $\beta = \sin^{-1}(r-h)/r;\ h < r$ being the height of the contact point from the ground. If the condition $h<r$ is satisfied, the reaction force at the contact point of the ball and the ground is $R = w - f_v$, where w is the weight of the ball and $f_v = F\sin\beta$ is the vertical component of F. This condition helps ball movement along the ground.

Control System Design

The industrial manipulator shown in Fig. 2(a) has five degrees of freedom in R-R-R-R-P configuration. The first joint has a vertical axis of rotation, whereas next three joints have horizontal axes of rotation. In the telerobotic golf design, only the first three joints were used. All three joints are rate controlled in joint co-ordinates $(\theta_1, \theta_2, \theta_3)$ in response to a motion command in Cartesian co-ordinates (x, y, z). The inverse kinematic transformation is given by

$$\theta_1 = \tan^{-1}(y/x) \quad (1)$$

$$\theta_2 = \tan^{-1}(c/z) - \cos^{-1}\ \frac{L_2^2 - L_3^2 + c^2 + z^2}{2L_2\sqrt{c^2+z^2}} \quad (2)$$

$$\theta_3 = \pi - \cos^{-1}\ (L_2^2 + L_3^2 - c^2 - z^2)/(2L_2L_3) \quad (3)$$

where $c = \sqrt{x^2+y^2} - L_1$, and Lj is the length of jth link. Independent servo actuators implement the feedback control law $u^j = K_v\left\{Kp(\theta^j_{in} - \theta^j_{out}) - \dot{\theta}^j_{out}\right\}$, where θ^j_{in}, θ^j_{out}, $\dot{\theta}^j_{out}$ are position input, position output, and velocity output of jth joint. Parameters K_p and K_v are position and velocity feedback gains. And, u^j is the power amplifier current input.

Constraint Checking and Safety Assurance

Having to deal with priori unknown maneuvers, telerobotic golf system requires thorough constraint checking of the remote operator position commands. All maneuverability constraints can be categorized into three groups as follows:

(a) Joint limits: All rotary joints have their working ranges. Once the remote operator command is transformed into joint co-ordinates using (1), (2), and (3). Joint positions are checked to verify that they remain within their respective working ranges $[\theta^j_{limit-}, \theta^j_{limit+}];\ j = 1, 2, 3$.

(b) Maximum reach: First joint is a vertical axis joint, thus, can be eliminated from the calculation of tool reach.

The maximum stretch of the manipulator with respect to the second joint is L_2+L_3. And, if the remote operator command (x, y, z) satisfies $L2 + L3 - \sqrt{(\sqrt{x^2 + y^2} - L_1)^2 + z^2} < \delta$, then, for any arbitrary command (x, y, z), the manipulator is safe from a distance of δ from the full-stretch singularity.
(c) Minimum putter height: The putter should always stay above the ground height h_{ground}. If the constraint $z > h_{ground}$ is satisfied, it is guaranteed that the putter does not come in contact with the ground.

All these constraints are checked at the remote operator terminal. Once all checks are passed, the command is sent to the local controller. This way, the safe operation of the telerobotic golf game is assured.

Remote Operator Interface
A keyboard interface was selected as it is the most common computer peripheral, which can be used as a teleoperator interface. This way, the telerobotic game could be played by anyone from anywhere in the world through his keyboard, after logging into the remote operator terminal in KAIST. The keys were assigned as shown in Fig. 3 to be consistent with the motion directions of the putter shown in Fig. 2(a).

Fig.3 Teleoperator's keyboard configuration

The key assignment is as follows
1) The four arrow keys were assigned to X-Y motion as ↑(+X:Forward), ↓(-X:Backward), ←(+Y:Left),and →(- Y:Right)
2) Vertical motion was assigned to ``tab" key(+Z:Up), and ``space bar"(-Z:Down)
3) 1, 2, and 3 numeric keys were assigned for step lengths of 1[mm], 3[mm], and 5[mm], respectively.

This key assignment was purely arbitrary, based on intuition. One rationale however is that this configuration is consistent with the natural finger positioning on the standard computer keyboard.

Challenges for the teleoperator
There are few difficulties that challenge the teleoperator stated as follows
1) Putter orientation: Putter is an extension of the prismatic fifth link, and the telerobot is operated using the first three joints. Having no motion at the fourth rotary joint, putter remains fixed at the same joint position relative to the third link. However, to assist the teleoperator, the fourth link is pre-adjusted to an approximate average vertical configuration within the golf-court. The prismatic fifth joint is also not operated, and it avoids the teleoperator rotate the putter the way he prefers.
2) Diagonal motions: Remote operator commands are limited to individual motions along X-Y-Z directions. There is no way to make other movements that combines these individual motions.
3) 2D visual feedback: Visual feedback provides only 2D view of the golf-court at a fixed camera position. It does not provide direct information of the relative putter position. And, no control of the camera positioning is provided.

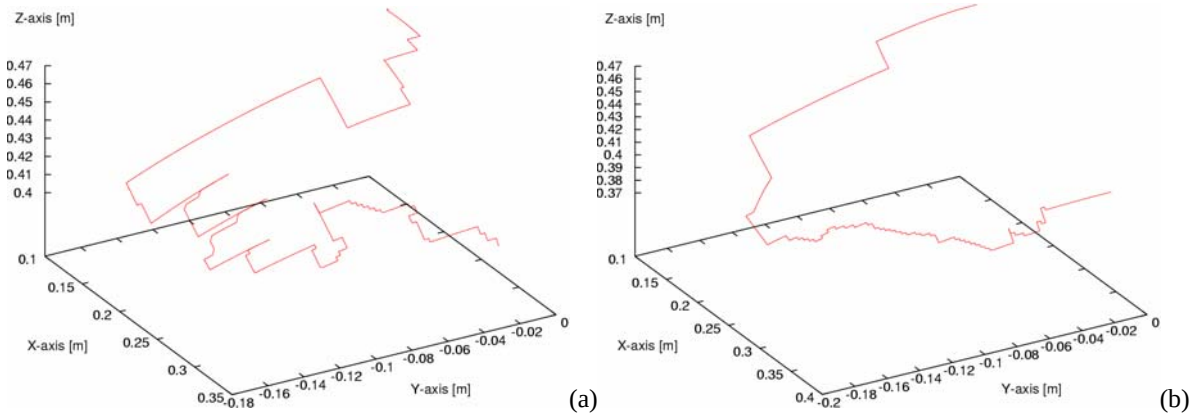
The teleoperators are expected to experience these challenges and deal with them by interactive learning.

3. IMPLEMENTATION

The remote operator terminal was implemented on RedHat Linux 8.0 with kernel version 2.4.20-19.8. The local controller was implemented on Debian GNU Linux 3.0, with real-time kernel 2.4.4-rtl. Due to network security reasons, local controller has not been assigned a global IP address, but it runs a virtual private network that issues a local IP address for the remote operator terminal. The visual feedback was implemented with Microsoft Net-meeting utility, with a single, inexpensive web-camera located at the telerobotic golf-court. Teleoperator's keyboard commands are checked against the working range of joints [-152,152](joint 1), [-45,140](joint 2), and [-142.5,142.5](joint 3) before sending to the local controller. There were eleven players involved from both KAIST and Saga University. They were explained that the operation is safe on their possible wrong commands, and that they are expected to reach the goal as quickly as possible, while learning by mistakes. Their courses of actions were recorded as movie clips, relayed, and evaluated.

3.1 Evaluation Criterion

The evaluation criterion was developed on the following measures of errors and skills. There were three recognized errors
1) E1: Hole error: If the player had to significantly change the direction of motion at the close vicinity of the hole, it is judged as a hole error.



(a) (b)

Fig.4 Trajectory of the putter, (a) with serious errors (b) an error-free trajectory

TABLE I-1: Test 1 statistics - for fast keyboard operators

	Errors (E1,E2,E3), skills(P1,P2), and timing		
User #	Trial #1	Trial #2	Trial #3
K1	(0,E2+,0),(0,0),(54)	(0,E2−,E3),(0,0),(51)	(0,0,0),(P1−,0),(43)
K3	(0,E2,E3),(0,0),(109)	(0,0,0),(P1−,P2−),(36)	(0,0,0),(P1+,0),(45)

TABLE I-2: Test 1 statistics - for slow keyboard operators

	Errors (E1,E2,E3), skills(P1,P2), and timing		
User #	Trial #1	Trial #2	Trial #3
K2	(0,0,0),(P1−,P2−),(66)	(0,0,E3),(0,0),(75)	(E1,0,0),(P1−,P−),(55)
K4	(0,E2−,0),(0,P2),(116)	(0,0,0),(0,P2+),(59)	(0,0,0),(P1,P2−),(52)
K5	(E1,E2+,E3+),(0,P2),(105)	(0,E2,0),(0,P2),(68)	(0,E2−,0),(0,P2),(59)
K6	(E1,E2+,E3),(0,0),(103)	(0,E2,E3),(0,0),(51)	(0,E2−,E3),(0,0),(49)
K7	(E1,E2+,E3),(0,0),(101)	(0,0,0),(P1−,P2−),(57)	(0,0,E3),(P1−,P2−),(71)

2) E2: Landing error. If the player had to make many moves off the ground before landing the putter behind the ball, it is judged as a landing error.
3) E3: Steering error: If the player failed to keep putting the ball from behind, it is judged as a steering error

And, there were two recognized skills
1) P1: Landing skill. If the player positioned the stick behind the ball without going through many moves off the ground, it is judged as a landing skill.
2) P2: Steering skill. If the player could keep steer the ball towards the hole, without going through other directions, it is judged as a steering skill.

3.2 Tests

Test 1: The first test aimed to investigate the interactive learning of human teleoperators, and reveal how they learn to enhance the performance. This test was carried out by seven players at KAIST(Korea). Each of them were given three trials starting with the same configuration as shown in Fig. 2(a). Figure 4 shows two trials in which the errors can be visualized and compared with an error-free trial.
Clearly, there are two categories of keyboard operators; fast operators and slow operators. The teleoperation characteristics significantly depend on this issue, and therefore, the performance were separately categorized in TABLE I-1, and TABLE I-2. Errors and skills are further evaluated and tagged as ``-"(slight), ``no sign"(considerable), and ``+"(serious). This grading was carried out by inspection of the movie clips. Errors and skills were further converted to numerical form by the following marking scheme:
1) slight errors or skills = 1 points
2) considerable errors or skills = 2 points
3) serious errors or skills = 3 points

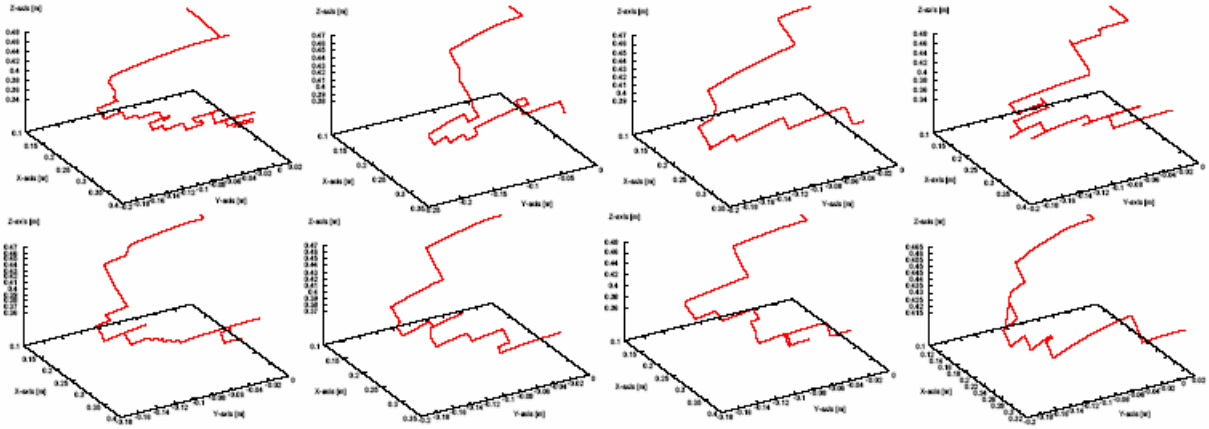


Fig.5 Trajectories at the visual feedback switching: Top - last trial with naked-eye visual feedback, Bottom - first trial with camera feedback

TABLE II: Test 2 statistics

Naked-eye visual feedback

	Errors (E1,E2,E3), skills(P1,P2), and timing (t)		
User #	Trial #1	Trial #2	Trial #3
S1	(E1,E2,E3),(0,0),(80)	(0,0,E3),(P1,0),(37)	(E1,0,E3+),(P1-,0),(86)
S2	(0,E2+,E3+),(0,0),(73)	(0,0,E3),(P1,0),(47)	(0,0,E3),(P1-,0),(50)
S3	(E1,E2,E3),(0,0),(78)	(E1,0,E3),(P1-,0),(46)	(E1,0,E3-),(P1+,0),(36)
S4	(E1,E2,E3+),(0,0),(86)	(0,E2+,E3+),(0,0),(60)	(0,E2+,E3+),(0,0),(65)

Camera visual feedback

	Trial #4	Trial #5	Trial #6
S1	(E1,0,E3),(P1-,0),(90)	(E1,0,0),(P1-,P2-),(80)	(0,0,0),(P1-,P2-),(80)
S2	(0,0,E3),(P1-,0),(61)	(0,0,E3-),(P1+,0),(37)	(0,0,0),(P1+,P2-),(36)
S3	(0,0,E3),(P1-,0),(97)	(0,0,E3),(P1-,P2),(63)	(0,0,0),(P1-,P2),(58)
S4	(0,E2-,E3+),(0,0),(71)	(0,E2-,E3+),(0,0),(81)	(0,0,E3),(P1-,0),(52)

Then, the error and skill counts were accumulated and graphed in Fig. 6(a).

Test 2: The second test aimed to investigate the key issues of the camera vision problem and how it affects the remote operator interaction and the entire performance of the telerobotic system. This test was carried out by four players at Saga University(Japan). These players made telnet-login to the remote operator terminal at KAIST, and performed six trials each. The first three trials of each player were carried out with naked-eye visual feedback. In order to get a consistent visual feedback, players positioned at the camera position in these trials. In their last three trials, they teleoperated the robot with the camera visual feedback. Figure 5 shows the trajectories of all four players at the time of visual feedback switching from naked-eye to camera. The performance is listed in TABLE II. The error and skill counts for the two tests are graphed in Fig. 6(b) and Fig. 6(c).

3.3 Results

Test 1:

The results in TABLE I-1, and TABLE I-2 can be interpreted as follows:

1) Fast-player K1, first tries to exploit (avoid errors) and then explore (exercise new skills). He recorded consistent improvement in successive trials. He explored landing skills (P1) and ended up with much better timing of 43[s]. He seems to be an already learned player (by other means of computer games). The fast-player K3, attempts exploitation and exploration simultaneously, taking a lot of risks. Not taking time to learn caused lot

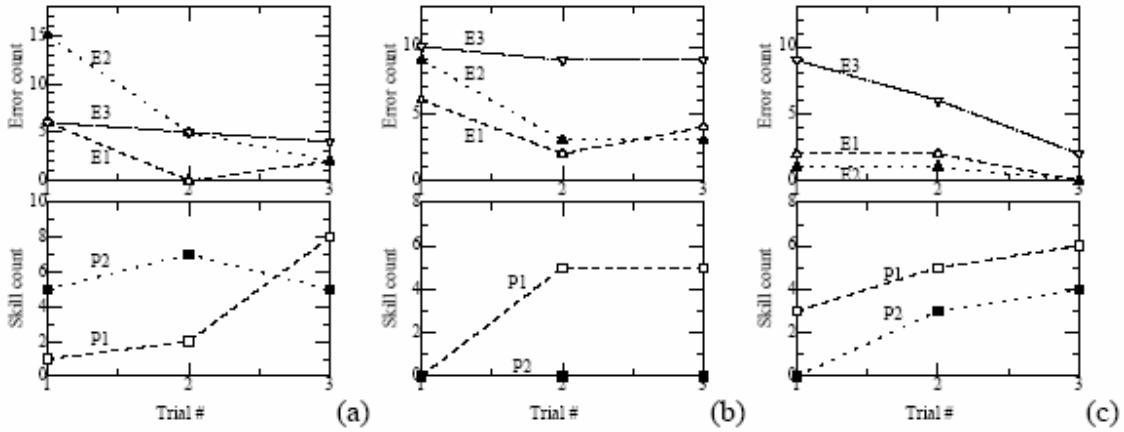


Fig.6 Error and skill counts: (a) Test 1, (b) Test 2: with naked-eye vision, and (c) Test 2: with camera vision

of errors in his very first trial. However, he has been extremely successful in the second trial both in landing (P1) and steering (P2) recording the overall minimum timing of 36[s]. His learning and adaptation is significantly fast.
2) The slow-players K4, K5, K6, and K7 have shown highly comparable and consistent statistics. Though their cautious behavior cost a significantly long time in the first trial due to going through all kinds of errors (E1, E2, E3). However, they are capable of quickly reducing hole error (E1) in the second trial onwards. They are inherently slow interactive, and records their best timing longer than that of the fast-players.
3) Unlike other slow-player, K7 shows exploring skills (P2) in his third trial, and cost additional time as it was not successful.
4) Slow-payer K2 shows somewhat already learned behavior comparable to the second trial of other slow-players.

Figure 6(a) verifies that the players learn to avoid errors very quickly, and that they learn new skills to properly operate the telerobot.

Test 2:
The results in Fig. 6(b) and Fig. 6(c) clearly show that there is no significant discontinuity of error and skill learning profiles due to switching from naked-eye vision to camera vision. The experience with the naked-eye vision is carried into the successive trial with the camera vision. This indicates to be an effective training procedure for human teleoperators in actual applications.

4 DISCUSSION

Following observations have been made during the trials.

1) Although the two-dimensional camera vision does not provide adequate feedback information for the teleoperator, he is capable of learning quickly by experience and guess-work. Practice with naked-eye vision significantly helps human teleoperator to accurately conceive the work-site geometry and also to exercise predictive control actions when he deals with camera vision.
2) Camera vision can be supplemented with a laser pointer attached to the putter, and beaming downward. The beam indicates the projection of the putter on the X-Y plane, which will be a useful guide for the teleoperator.
3) The round trip transmission delay was measured by a ``ping-test" as 14[ms]/20[ms]/28[ms] in the minimum/average/mean deviation format. Visual feedback adds more time to these statistics. This delay has been slightly noticed by almost all players. Yet, they did not experience any difficulty in practicing their predictive control actions.
4) Predictive control is attributed to teleoperation. As predictive control is based on the velocity of motion, it is necessary to maintain a continuous motion to exploit cognitive prediction skills of the teleoperator. It was clearly observed that many operators prefer to use small step lengths (1[mm]-3[mm]) and keep issuing commands and maintain a velocity throughout the operation. On the other hand, they dislike move-and-wait mode of control as waiting significantly retards their predictive control capabilities.
5) Key configuration of the keyboard should comply with the telerobot's motion directions. Using arrow keys for X-Y motion is effective, whereas ``tab" and ``space bar" are not. For Z axis motions, a better configuration would be ``A" and ``Z" alphabet keys, which are the same keys that are used in most computer games.
6) More crucial factor that consumes time is wrong commands due to wrong key strokes. All players demonstrated this confused interaction with the keyboard intermittently. However, with more appropriate key

assignment, and also with practice, this problem can be completely solved.

7) Without being able to perceive the height of the ``putter'' from the camera view in Fig. 2(a), there was a slight tendency that the ball being putted too high off the ground, violating the condition $h < r$ in Fig. 2(c). It produces an excessive force $R = w + f_v$ on the ground, that would be disastrous. To avoid this, either camera angle could be adjusted, or a local force feedback could be implemented.

8) To further improve controllability, fourth link can also be synchronously controlled with the second and third joints in order to compensate the deflection of putter orientation due to the motions of other rotary joints. This way, the putter will stay vertical, giving a better response for the teleoperator.

9) Task oriented camera position control would be an effective way of exploiting the vision information. It would also be an effective alternative to sophisticated graphics-based techniques.

5 CONCLUSION

Human teleoperators learn and adapt very quickly to a properly designed teleoperator interfaces. A very few trials is enough for them to learn how to avoid errors and learn new skills even without sophisticated graphics-based interfaces. A general learning pattern is to exploit error avoidance first, and then explores new skills despite the delay and vision problems. A significant fraction of teleoperators show a very steady and consistent learning pattern. Although two-dimensional camera visual feedback significantly affects teleoperator performance, training with naked-eye vision can significantly help them to exercise accurate teleoperations. This could be a very effective training procedure for human teleoperators before they are deployed for actual teleoperations. Keyboard interface has shown to be very effective and easy to learn with, as it provides the operator a quantitative measure about his own commands. It helps him to predict the movements of the telerobot more accurately. To further help the prediction accuracy, small step sizes and a more continuous motion are useful. Simple techniques such as pointed beams (laser) and task-oriented camera position control can be incorporated to help the teleoperator with vision problems.

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Butler: A Visitor Guide Robot

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Abstract: This paper describes the major components of software architecture of an autonomous visitor guide robot with the brief explanation of its hardware system. This robot, "Butler," was deployed in a real office environment, Intelligent Robot Research Center at KIST, where it guided many visitors successfully. To make the robot navigate the office and interact with visitors without problems, many challenges such as navigation in dynamic environments and interaction through various methods should be overcome. In this paper, the solutions for those problems are illustrated and our conclusion about this project is discussed.

Keywords: guide robots, mobile robots, service robots, navigation, HRI

1 INTRODUCTION

This paper describes Butler, a visitor guide robot, about the major components of software architecture of an autonomous visitor guide robot with the brief explanation of its hardware system. This robot was deployed in a real office environment, Intelligent Robot Research Center at KIST, where it guided many visitors successfully. To make the mobile robot operate safely and robustly in the office, many functions such as localization, collision avoidance, and path-planning are essential as well as a proper coordination of those functions. A user friendly interface is another very important part when developing a guide robot which needs to interact with people continually. Butler supports various easy-to-use interfaces like voice, touch screen, PC vision.

The robot's major components can be thought as three parts like the following:

Hardware: Butler's mobile platform adopted omni-directional wheel mechanism; all wheels are castors. Modularization based on the network-based system was adopted when implementing the controller systems. The shape and the height of the robot were also determined by considering user's convenience.

Navigation: Butler's navigation modules can be divided into three main parts: localization, obstacle avoidance, and path-planning. Not only every part should do well its own function, but also all parts should be controlled to cooperate with one another properly by well-organized coordination architecture.

Human-Robot Interface (HRI): We introduced and implemented a multi-modal HRI system, which supported various HRI methods such as voice, vision, touch screen GUI. The system was designed so that all types of human-robot interaction can work simultaneously in both directions.

In the following sections, we will discuss each part in more detail.

2. HARDWARE SYSTEMS

Butler's omni-directional wheel mechanism enables the robot to move to every direction with the redundant freedom of its orientation at any time. This function makes it possible for the robot to guide the visitor to a given position with simultaneously looking him/her in the face for continuous interaction. For the omni-directional mechanism, the robot employed three castor wheel type since omni-directional mobile robot with three castor wheels is more efficient than omni-directional mobile robot with Swedish wheels. Two motors for each castor were assigned and total six motors were used to avoid any singularity which happens in this type robot when less than four motors are used and to give redundant actuation which provides mobile system

(a) (b)

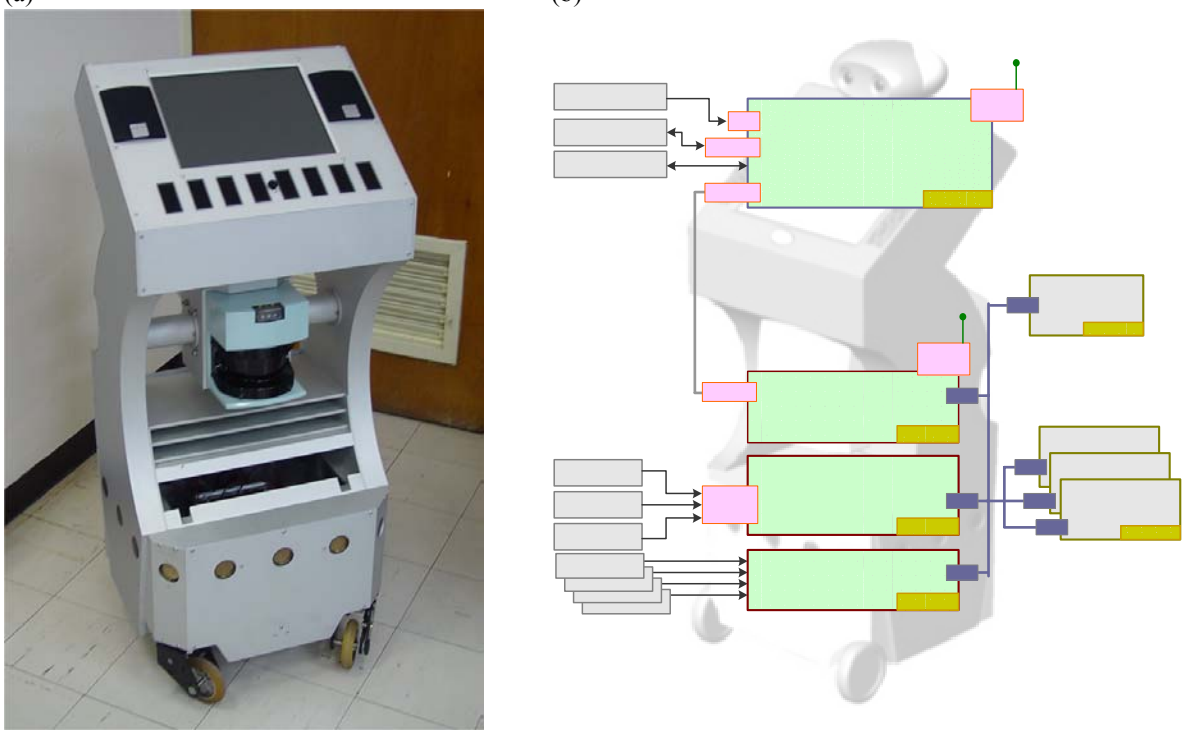

Figure 1. (a) Butler. (b) The architecture of controller.

with many beneficial characteristics such as good load distribution and fault-tolerant capability[5].

When it comes to Butler's electrical equipments, it consists of 2 major parts; the human interface part and the robot control part. Human interface was implemented with a notebook equipped with a touch screen, a microphone, a USB camera and speakers in the kiosk-like mobile robot. The robot control part was developed with a networked-based distribution systems using CAN(Controller Area Network) with maximum speed of 1 MHz. Advantages of the network-based architecture are parallel developing process, isolation of a problem, easy modification or repair. The networked based distribution systems are composed of hardware-independent modules such as a navigation-localization module, a central control module and a sensor module. Functions for each module and the overall controller system configuration are shown in figure 1(b).

3. NAVIGATION

3.1 Kinematics for control

From the relation between the mobile robot's velocity $(\dot{x}, \dot{y}, \dot{\theta})$ and each castor's joint angle, joint angle velocity and wheel velocity $(\beta, \dot{\beta}, \dot{\varphi})$ in figure 2, the following equations can be obtained for all the castors[x].

$$
\begin{aligned}
d\dot{\beta} &= -\cos(\alpha+\beta)\dot{x} - \sin(\alpha+\beta)\dot{y} - (d+\ell\sin\beta)\dot{\theta} \\
r\dot{\varphi} &= \sin(\alpha+\beta)\dot{x} - \cos(\alpha+\beta)\dot{y} - (\ell\cos\beta)\dot{\theta}
\end{aligned}
\tag{1}
$$

Thus, the matrix equation of the robot's inverse kinematics follows

$$
\begin{pmatrix} d_1\dot{\beta}_1 \\ r_1\dot{\varphi}_1 \\ d_2\dot{\beta}_2 \\ r_2\dot{\varphi}_2 \\ d_3\dot{\beta}_3 \\ r_3\dot{\varphi}_3 \end{pmatrix} = \begin{pmatrix} -\cos(\alpha_1+\beta_1) & -\sin(\alpha_1+\beta_1) & -(d_1+\ell_1\sin\beta_1) \\ \sin(\alpha_1+\beta_1) & -\cos(\alpha_1+\beta_1) & -(\ell_1\cos\beta_1) \\ -\cos(\alpha_2+\beta_2) & -\sin(\alpha_2+\beta_2) & -(d_2+\ell_2\sin\beta_2) \\ \sin(\alpha_2+\beta_2) & -\cos(\alpha_2+\beta_2) & -(\ell_2\cos\beta_2) \\ -\cos(\alpha_3+\beta_3) & -\sin(\alpha_3+\beta_3) & -(d_3+\ell_3\sin\beta_3) \\ \sin(\alpha_3+\beta_3) & -\cos(\alpha_3+\beta_3) & -(\ell_3\cos\beta_3) \end{pmatrix} \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix}
\tag{2}
$$

Using the equation (2), we can calculate joint angle velocity and wheel velocity of each castor for a given mobile robot velocity. Moreover, for robot's dead reckoning, this equation is used. The above equation could be expressed like

$$
\dot{\mathbf{q}} = \mathbf{A}(\mathbf{q})\dot{\mathbf{x}} .
\tag{3}
$$

To get the robot's velocity from encoder data of each castor, the following equation is used.

$$\dot{\mathbf{x}} = \mathbf{A}^{\#}(\mathbf{q})\dot{\mathbf{q}} \tag{4}$$

where $\mathbf{A}^{\#}$ is pseudo-inverse of **A.**
Then, **x** is the minimum norm solution among all solutions provided by the equation (3).

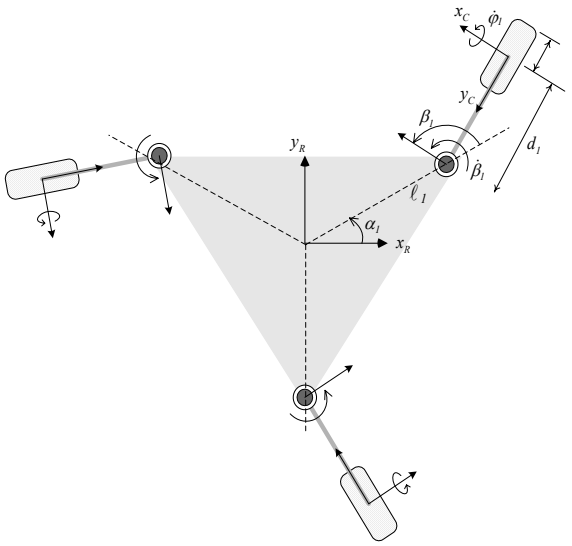

Figure 2. Configuration of three castor wheel mechanism.

3.2 Localization

Localization is to estimate a robot's coordinates in x-y-θ space, where x and y are the coordinates of the robot in a 2D Cartesian coordinate system, and θ is its orientation. Butler employed Markov localization, whose reliability and practical usefulness has been verified through the real applications for the tour guide robot in the museum[2]. Generally, the algorithm needs a lot of calculation time since it maintains probabilistic beliefs for whole possible states. Several remedies have been proposed to overcome this problem by the author who proposed the algorithm. Butler uses those remedies like selective update, various filters, and sensor lookup table models[2]. In addition, Butler employs an *active area update* technique. This technique is very useful in that unexpected areas in the map are removed at the beginning. Thus, it efficiently relieves the burden of calculation depending on the robot's task. For example, whole map area is divided into 5 small areas in the Figure 3. When the butler's mission is to guide a visitor into the front of door of a correspondent person, in this case, the robot doesn't have to go inside the rooms(The controller works in that way). Therefore, the active areas become Area 3 and Area 4. It means that the robot tries to find its location in those active areas. As you can guess from the size of the areas in the Figure 3, it can cut down, in this example, the calculation time of localization to about one third of the time that takes when it uses whole area.

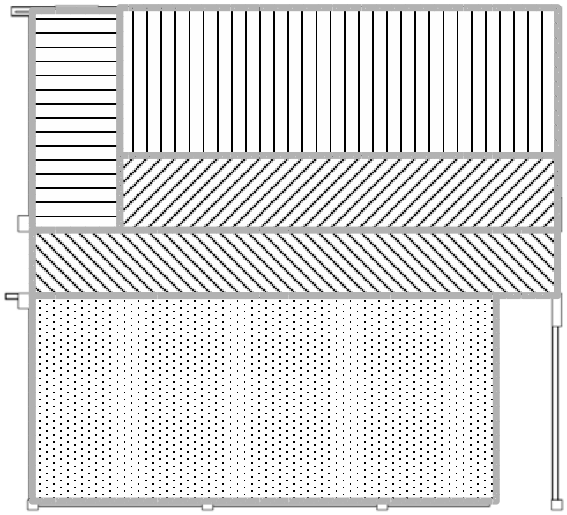

Figure 3. Small area example

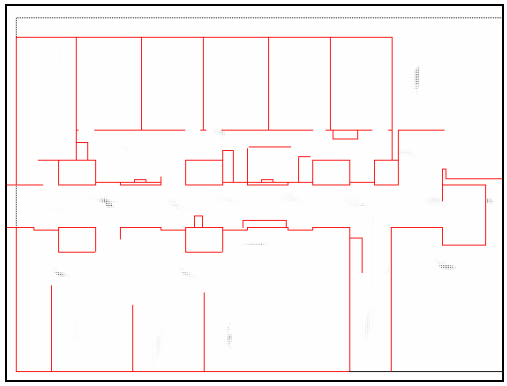

Figure 4. Markov localization from 9 laser scan data

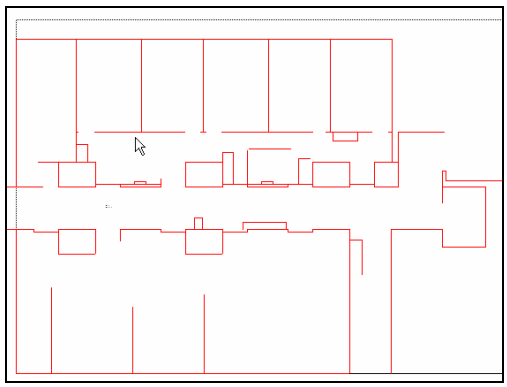

Figure 5. Markov localization from 18 laser scan data

3.3 Path-Planning

Butler's path planner is based on dijkstra's algorithm, a well-known shortest path finding algorithm. The path planner generates paths from one node to another. The result paths are made in the form of sequential node numbers. For example, if the robot's near node is 8 and the destination node is 4 in figure 6, then the result will become 8-9-2-3-4. Node information such as node's location and the distances between nearby nodes is saved in advance.

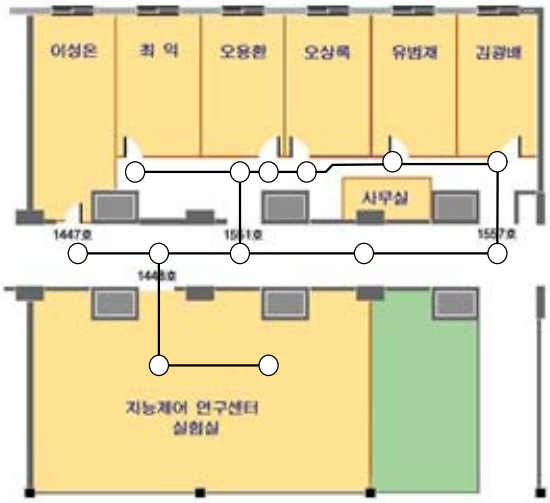

Figure 6. Node connections for path planning

3.4 Local navigation (Obstacle avoidance)

For local navigation between nodes, the Generalized Voronoi Graph(GVG)[1] is adopted. GVG is an effective tool for the guide robot because of its two major advantages. First, the GVG is a sensor based navigation which can adaptively react on the dynamic changes of the environment. For example, there could be a sudden human appearance and the robot should avoid the person reactively. This behavior can be implemented by using the incremental GVG construction algorithm which uses current sensor data for the next motion generation. Second, the GVG can be used for a semi-unstructured environment such as indoor corridor-like environment.

As a result, the GVG based navigation makes the robot move following the middle of empty space like in figure 7.

4. HUMAN ROBOT INTERFACE

Because Butler is designed to work as a service robot, its human-user interface (HRI) organization is an important part of our system. Working in the office environment, Butler usually interacts with the people, who are not robotic experts.

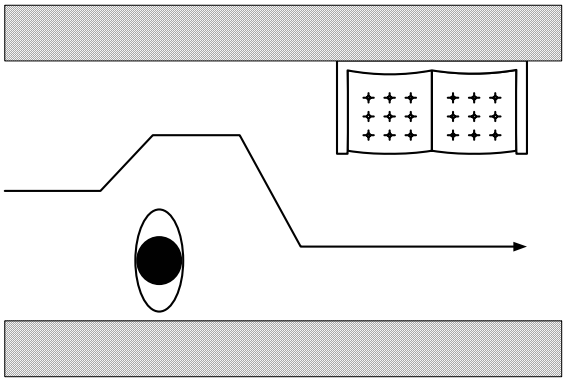

Figure 7. Expected trajectory of GVG

A good HRI system is the key for this robot to success. In this paper, we introduce and implement a multi-modal HRI system, that support all common HRI methods such as voice, vision, touch screen GUI. Moreover, we also design the Internet-based HRI, where users can interact with robot by using haptic devices with force feedback or by a professional web-based program. The system is designed so that all types of human-robot interaction can work simultaneously and in both directional. As users command Butler to do something, it can provide the information to the users via Voice, Vision, and the Internet. Besides directly interact with users, Butler also works as a mean to communicate users. After being asked about some one it knew, Butler searches the information and connects the user to the required person and allows communication (chat, voice, video conference) between them through its Internet HRI part.

Figure 9 shows the structure of the HRI system. We separate the interface part and the controlling part in two separate platforms and connect them via wireless network and serial communication. The internet-based HRI systems are existed in both platforms to support directly controlling of the hardware system or merge multi-modal interaction in the same input analyzing block.

Our experiments on the Butler system in the real office environment show that the interface is very convenient to the users. Butler show out to be good at understanding the requirements from the users and provides guiding services and informative, useful feedbacks via voice, video and GUI interface. Butler successfully guides people to the required places in most of the cases. Experiments with normal users also prove that the simultaneous multi-modal interaction system may improve the ability of exploring the system.

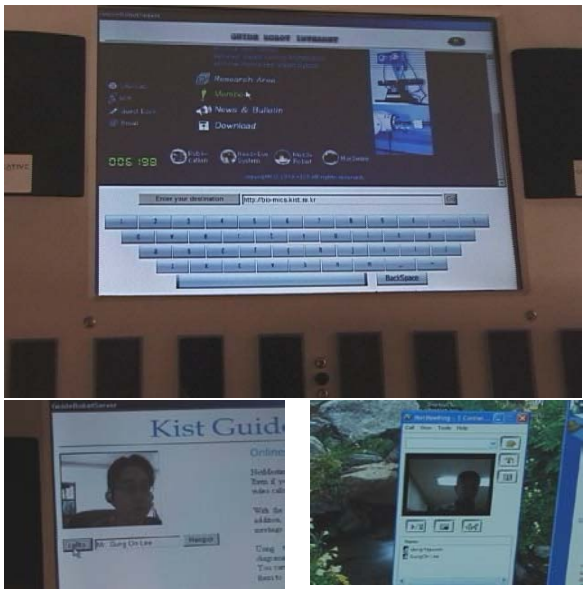

Figure 8. HRI (a) Internet service through touch screen (b,c) Online chat service through voice and pc camera.

Using robot as a tool to communicate with people before guiding users via direct multi-media conferencing system seems stranger at first but turn out to be good in the long term experiments. We are also investigating another communication system to improve the interaction ability of our robotic system.

5. CONCLUSION

This paper described the hardware and the software of a visitor guide robot, which was successfully installed in the Korea Institute of Science and Technology. New ideas and solutions for challenges arising from the real guidance were addressed with overall explanation of each part. Through many real guidance demonstrations, we could have the following conclusions and future work includes those subjects.

1. The robot needs a fault-finding or a self-diagnosing mechanism to make a fully autonomous robot in the case it loses its location completely or its batter level becomes low.

2. Voice service is much helpful than the service from the screen. Visitors usually do not like to stay near the robot when it moves. Thus, information through the screen was not easy to be given to the visitors when the robot is in the motion. Furthermore, people seemed to prefer talking to the robot more to touching it when they wanted to give it some order.

3. More friendly shape is preferable. This robot interacts with people who are generally not familiar with robotic systems. A friendly user-interface should be considered as important as the robot's functions when the robot needs to be used in public.

4. A good mapping method should be implemented. If the robot's working environment changes, we should reproduce a map for the robot. This could be a very time-consuming task when we do not have any CAD data for the new environment. Future research includes the integration of SLAM(simultaneous localization and mapping) which became already one of very popular research issues.

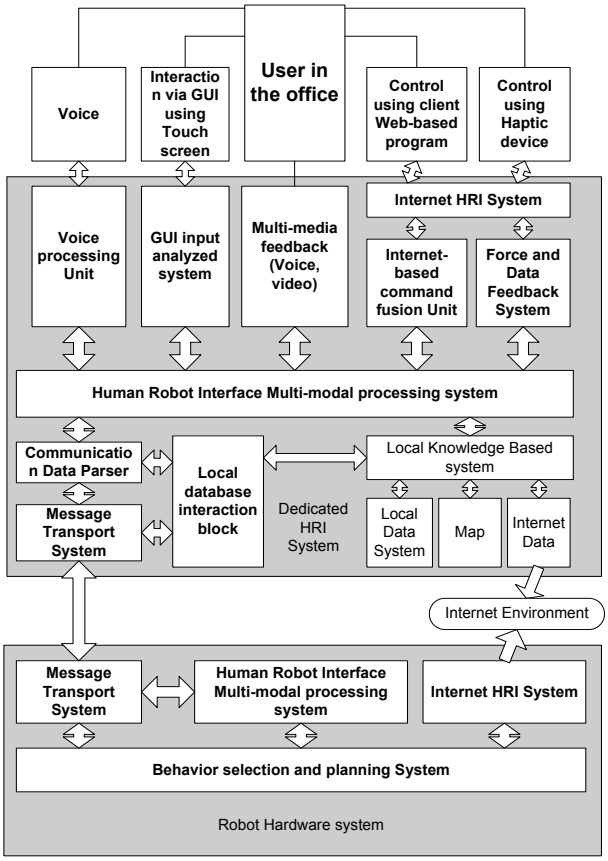

Figure 9. The structure of HRI system

Figure 10. Guiding a visitor in the office environment

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BASIC CONSIDERATION ON PRESHAPING FOR CAPTURING A ROTATIONAL OBJECT

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Abstract: Preshaping is an important issue for a robot hand to grasp a moving object successfully. Generally, a moving object in 3D space has rotational motion as well as translational one. This study discusses dynamic preshaping issue for such an object changing the posture momentarily. In this paper, we focus on determining the timing for grasping the object. We first show a strategy to extract candidates of timing for grasping. We also verify the proposed strategy by experiments using a high speed hand with the assistance of a high speed vision.

Keywords: preshaping, high speed capturing robot, rotational object

1. INTRODUCTION

When grasping an object by hand, human makes approach to the object with an appropriate preshape of finger, so that he (or she) can naturally make contact with it. Such preshaing issues are also important for a robot hand to grasp an object, especially either the robot hand or the object is moving quickly. There have been various works [1]–[11] concerning preshaping issues. Bard and Troccaz [1] have extracted the shape of object by vision and determined the hand preshape based on the information. Kang and Ikeuchi [2] have computed various points leading to a successful grasping with the help of vision, and found the finger tip level preshaping where each finger tip easily reaches the computed point. These works suppose that the object is stationary or moving slowly. Under such a quasi-static condition, so far, they have handled the issue for determining the preshape of robot hand.

On the other hand, with the increase of sensing speed, it is possible to chase the moving object by a high speed vision. For example, Namiki and others [9] have realized a dynamic catching of a sphere object by the combination of the 1ms-vision and a high speed robot hand. Higashimori and others [11] have discussed the design of robot hand suitable for capturing a moving object under the 100G acceleration. Under such a high acceleration, the preshaping issue is really important. Without an appropriate preshaping, it is impossible to successfully catch an object. These works, however, treat simple objects only, such as sphere or circle, as shown in Fig.1(a).

Now, suppose that a robot hand captures an object whose shape much differs from phase to phase, as shown in Fig.1(b). For such an object, we have to consider the orientation of object as well as its position. This paper discusses the preshaping issue for such an object. Especially, we are interested in the timing issue on how to determine the time appropriate for successfully catching the object, by supposing a high speed vision.

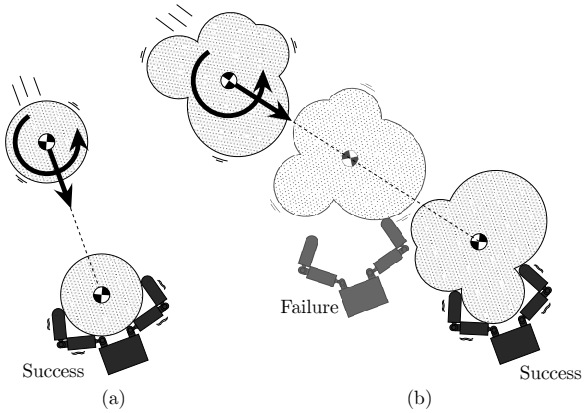


Fig. 1 Capturing a rotational object

This paper is organized as follows: We show the problem formulation in chapter 2, and discuss a strategy in chapter 3 how to determine the position of hand by assuming that the object moves with constant translational and rotational velocities. We verify the idea through a couple of experiments in chapter 4. We give some discussions on the relationship between the rotational velocity of object and that of finger joint, in chapter 5, before concluding.

2. PROBLEM FORMULATION

Suppose the two-dimensional robot-object system as shown in Fig.2, where Σ_R, Σ_g, Σ_h, θ_g, θ_h, $\boldsymbol{p}_g$, and $\boldsymbol{p}_h$ denote the absolute coordinate system, the object coordinate system, the hand coordinate

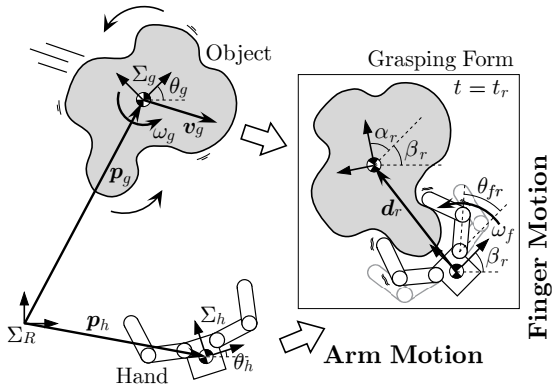


Fig. 2 Coordinate system

system, rotational angle of object with respect to Σ_R, rotational angle of hand with respect to Σ_R, the position vector of object with respect to Σ_R, and the position vector of hand with respect to Σ_R, respectively. Let $\boldsymbol{v}_g$ and ω_g be the translational velocity and the rotational velocity of object, respectively. We suppose that $\boldsymbol{p}_g$, $\boldsymbol{p}_h$, θ_g, θ_h, $\boldsymbol{v}_g$, and ω_g are all known.

Problem Formulation: Determine the time $t = t_r$, so that the following conditions can be satisfied.

$$\begin{pmatrix} \boldsymbol{p}_h(t) \\ \theta_h(t) \end{pmatrix} = \begin{pmatrix} \boldsymbol{p}_g(t) \\ \theta_g(t) \end{pmatrix} - \begin{pmatrix} \boldsymbol{d}_r \\ \alpha_r \end{pmatrix} \quad (1)$$

$$\theta_h(t) = \beta_r \quad (2)$$

where $\boldsymbol{d}_r$, α_r, and β_r are the constants showing the relative position between the hand and the object at the goal, the relative orientation between them, and the absolute posture of hand, respectively.

This paper focuses on the timing issue but not on the finger shape at the goal. As for hand, we suppose that each finger has only one rotational degree of freedom at the base and both fingers start to rotate at $t = t_r - t_f$ with ω_f, where

$$t_f = \frac{\theta_{fr} - \theta_f(0)}{\omega_f} \quad (3)$$

where θ_{fr} and $\theta_f(0)$ are the reference angle of finger and the initial angle, respectively.

3. STRATEGY TO DETERMINE TIME FOR GRASPING

In this chapter, supposing that the hand has two translational d.o.fs and one rotational d.o.f at its base, we discuss the issue for determining the time for capturing an object with rotating as well as

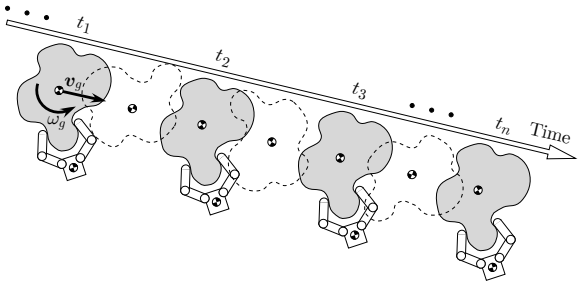


Fig. 3 Timings for grasping a rotational object

translating motions. Since the object is assumed to move with constant velocity, we can express the position and the orientation with respect to time as follows:

$$\begin{pmatrix} \boldsymbol{p}_g(t) \\ \theta_g(t) \end{pmatrix} = t \begin{pmatrix} \boldsymbol{v}_g \\ \omega_g \end{pmatrix} + \begin{pmatrix} \boldsymbol{p}_g(0) \\ \theta_g(0) \end{pmatrix} \quad (4)$$

where t, $\boldsymbol{p}_g(0)$ and $\theta_g(0)$ are time, initial position and orientation, respectively. From eq.(1), (2), and (4), we can obtain candidates of time for capturing as follows:

$$t_n = \frac{\alpha_r + \beta_r - \theta_g(0)}{\omega_g} + \frac{2n\pi}{|\omega_g|} \quad (n = 0, 1, 2, \cdots) \quad (5)$$

where n denotes non-negative integer. From eq.(5), we can see that a candidate time appears periodically, as shown in Fig.3. We now suppose that both translational and rotational speeds are constrained by their upper limitations, respectively, as follows:

$$\begin{pmatrix} \|\dot{\boldsymbol{p}}_h(t)\| \\ |\dot{\theta}_h(t)| \end{pmatrix} \leq \begin{pmatrix} V_h^{\max} \\ \Omega_h^{\max} \end{pmatrix} \quad (6)$$

where $V_h^{\max}$ and $\Omega_h^{\max}$ denote the maximum translational speed and rotational speed, respectively. Now, a natural question is how to choose an appropriate time among all candidates of time. Suppose that the hand is taking its capturing action for the selected time t_n, as shown in Fig.4, where $\boldsymbol{p}_h^r(t_n) = \boldsymbol{p}_g(t_n) - \boldsymbol{d}_r$ denotes the reference position of hand at time t_n. At the capturing point, the moving distance and the rotational angle of hand are given by $\|\boldsymbol{p}_h^r(t_n) - \boldsymbol{p}_h(0)\|$ and $|\beta_r - \theta_h(0)|$, respectively. The necessary condition for the hand to reach the goal position is given by

$$t_n \geq t_h(t_n) \quad (7)$$

$$t_n \geq \frac{|\beta_r - \theta_h(0)|}{\Omega_h^{\max}} \quad (8)$$

where

$$t_h(t_n) = \frac{\|\boldsymbol{p}_h^r(t_n) - \boldsymbol{p}_h(0)\|}{V_h^{\max}} \quad (9)$$

We further suppose the following constraint for hand, as shown in Fig.5, where $\boldsymbol{p}_h^{\min}$ and $\boldsymbol{p}_h^{\max}$ denote the minimum and the maximum movements

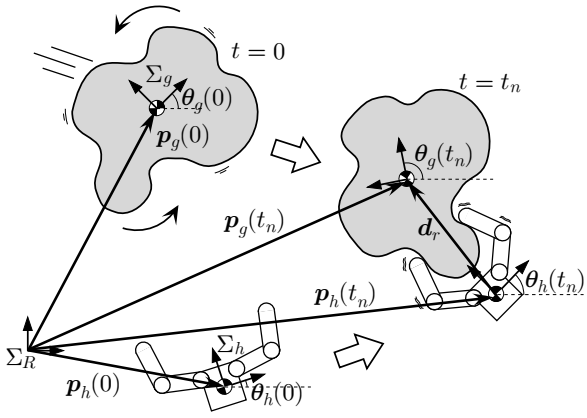


Fig. 4 A time t_n for grasping a rotational object

of hand, respectively.

$$\boldsymbol{p}_h^{\min} \ \leq \ \boldsymbol{p}_h(t) \ \leq \ \boldsymbol{p}_h^{\max} \tag{10}$$

Accordingly, the goal position of hand receives the following constraint as well.

$$\boldsymbol{p}_h^{\min} \ \leq \ \boldsymbol{p}_h^r(t) \ \leq \ \boldsymbol{p}_h^{\max} \tag{11}$$

Based on the above consideration, we are allowed to choose the capturing time from the following assemble $\mathcal{T}_r$:

$$\mathcal{T}_r = \left\{ t_n \;\middle|\; \begin{array}{l} t_n = \frac{\alpha_r+\beta_r-\theta_g(0)}{\omega_g} + \frac{2n\pi}{|\omega_g|} \\ \qquad (n=0,1,2,\cdots) \\ t_n \geq t_h(t_n) \\ t_h(t_n) = \frac{\|\boldsymbol{p}_h^r(t_n)-\boldsymbol{p}_h(0)\|}{V_h^{\max}} \\ t_n \geq \frac{|\beta_r-\theta_h(0)|}{\Omega_h^{\max}} \\ \boldsymbol{p}_h^{\min} \ \leq \ \boldsymbol{p}_h^r(t_n) \ \leq \ \boldsymbol{p}_h^{\max} \end{array} \right\} \tag{12}$$

Fig.5 shows the relationship between the constraint condition and the assemble $\mathcal{T}_r$. Generally, possible candidates for capturing time increase as either the translational velocity decreases or the rotational velocity increases.
On the other hand, we have to choose one time among candidates for real application. This need additional constraint, for example:

(a) The minimum (or maximum) time between sensing and grasping

$$t_r = t_n \left| \begin{array}{l} \min \ \{t_n\}, t_n \subset \mathcal{T}_r \\ (\max) \end{array} \right. \tag{13}$$

(b) The minimum (or maximum) distance of hand movement

$$t_r = t_n \left| \begin{array}{l} \min \ \{\|\boldsymbol{p}_h^r(t_n) - \boldsymbol{p}_h(0)\|\}, t_n \subset \mathcal{T}_r \\ (\max) \end{array} \right. \tag{14}$$

(c) The minimum (or maximum) waiting time at the capturing point

$$t_r = t_n \left| \begin{array}{l} \min \ \{t_n - t_h(t_n)\}, t_n \subset \mathcal{T}_r \\ (\max) \end{array} \right. \tag{15}$$

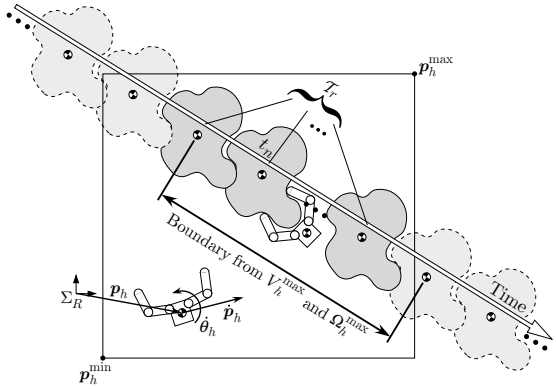


Fig. 5 A set of candidate $\mathcal{T}_r$

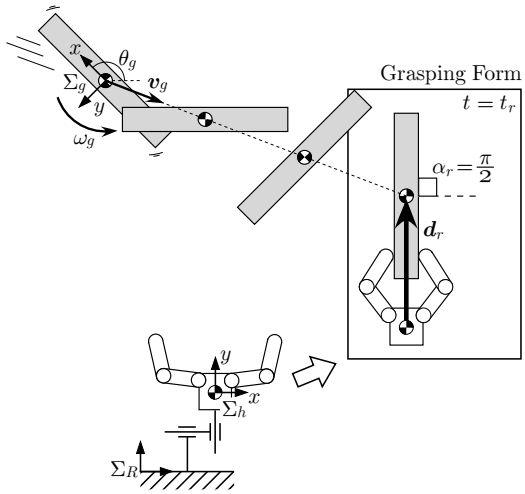


Fig. 6 Capturing a stick-shaped object using a 2-DOF translational arm/hand

We would note that these additional constraints should be slightly modified based on the shape of object and the mechanism of arm. We would also note that the second term of eq.(5) may change according to how often the combination of graspable points appear during one rotation.

4. EXPERIMENTS

Fig.6 shows the experimental system where the base of hand can move in two d.o.f (the x and y directional motions), and a high speed vision is installed to detect the position and velocity of object.

4.1 Capturing a stick-shaped object

Suppose the arm/hand system as shown in Fig.6, where $\theta_h = 0$. Under this mechanical configuration, ineq.(6) and eq.(9) can be converted as follows:

$$\left(\begin{array}{c} |\dot{p}_{hx}(t)| \\ |\dot{p}_{hy}(t)| \end{array} \right) \leq \left(\begin{array}{c} V_{hx}^{\max} \\ V_{hy}^{\max} \end{array} \right) \tag{16}$$

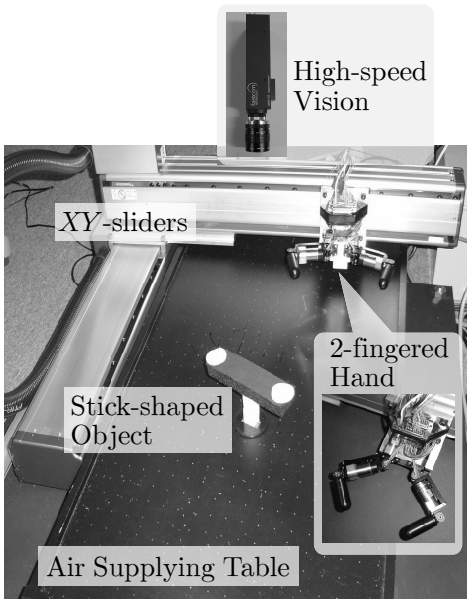


Fig. 7 An overview of experimental system

$$t_h(t_n) = \max\left\{ \frac{|p_{hx}(t_n) - p_{hx}(0)|}{V_{hx}^{\max}}, \frac{|p_{hy}(t_n) - p_{hy}(0)|}{V_{hy}^{\max}} \right\} \quad (17)$$

where the x direction is chosen so that the direction may be coincided with the longitudinal direction of object. The goal position and posture of object are given as follows:

$$\begin{pmatrix} \boldsymbol{p}_h(t) \\ 0 \end{pmatrix} = \begin{pmatrix} \boldsymbol{p}_g(t) \\ \theta_g(t) \end{pmatrix} - \begin{pmatrix} \boldsymbol{d}_r \\ \frac{\pi}{2} \end{pmatrix} \quad (18)$$

where $\alpha_r = \pi/2$ and $\boldsymbol{d}_r = [0, d]^T$ are chosen, respectively. Furthermore, by supposing that both edges are allowed to be grasped for this particular object, eq.(5) can be replaced by the following.

$$t_n = \frac{\frac{\pi}{2} - \theta_g(0)}{\omega_g} + \frac{n\pi}{|\omega_g|} \quad (n = 0, 1, 2, \cdots) \quad (19)$$

4.2 Experimental system

Fig.7 shows the experimental system where a high speed vision (iMVS-155 FastCom Technology Co. [12]) is implemented in the height of 1[m] from the table and the air is regularly supplied from the surface of table so that we can reduce the friction between the object and the table. We intentionally attach two white markers to the object so that the vision system can recognize both position $\boldsymbol{p}_g(t)$ and orientation $\theta_g(t)$ of object. The base of hand is measured by the encoder equipped with the motor for driving the slider. The hand is constructed by two fingers [13] and can produce the maximum rotational speed with ω_f=14 [rad/s]. The slider can move within 400[mm]×400[mm] with the maximum speed of 1000[mm/s] in each axis.

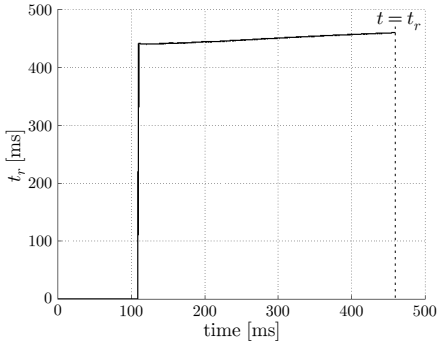


Fig. 8 The estimated time for grasping with respect to time

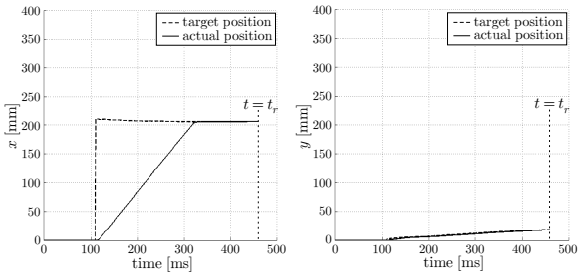
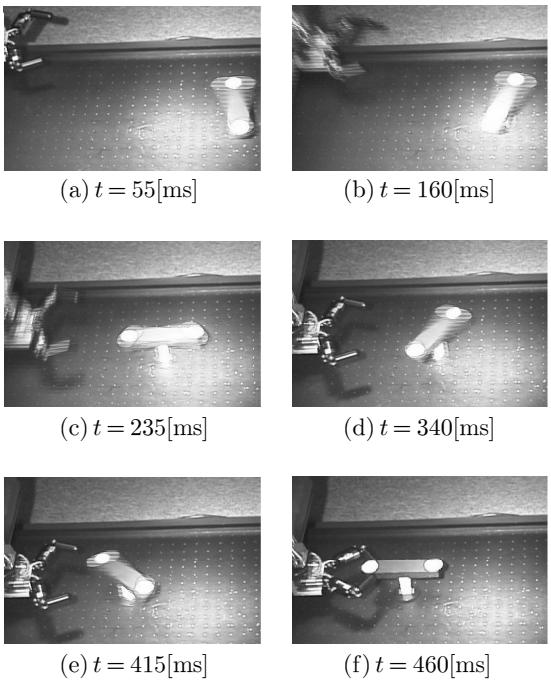


Fig. 9 Target and actual positions of the hand

4.3 Experimental results

The first thing to do is to estimate $\boldsymbol{v}_g$, ω_g, $\boldsymbol{p}_g(0)$, and $\theta_g(0)$, by utilizing the vision information. By continuously computing those parameters, we obtain the newest information on candidates for grasping, where we set that $\theta_f(0) = 0.44$[rad], $\theta_{fr} = 0.93$[rad], and $t_f = 35$[ms], respectively. Fig.8 shows an example of estimated time at grasping point where $|\dot{p}_{hx}| = 1000.0$[mm/s], $|\dot{p}_{hy}| = 1000.0$[mm/s], $\boldsymbol{p}_h^{\min} = [0.0, 0.0]^T$[mm], $\boldsymbol{p}_h^{\max} = [400.0, 400.0]^T$[mm], $\boldsymbol{p}_h(0) = [0.0, 0.0]^T$[mm], $\boldsymbol{d}_r = [0.0, 140.0]^T$[mm], $\boldsymbol{v}_g = [12.4, 618.9]^T$[mm/s], and $\omega_g = 17.47$[rad/s], respectively. We would note that the condition (14) is utilized for uniquely determining the time. From Fig.8, we can see that t_r is converging after $t \geq 110$[ms], while it includes some small disturbance. Fig.9 shows the trajectory of the change of the goal position and actually tracked position, respectively. We can see that the x and y directional goal positions can be successfully estimated at $t = 350$[ms] for the x direction and at $t = 110$[ms] for the y direction, respectively. Fig.10 and Fig.11 show a series of motion during the grasping motion. At first, the hand keeps stationary at the waiting position, while the vision system continuously compute the goal position and orientation (Fig.10(a)). By taking the closing time of hand, the hand moves to the target position (Fig.10(b)-(d)) and waits until the object comes (Fig.10(e), Fig.11(a)). After the grasping



(a) $t = 55$[ms] (b) $t = 160$[ms]
(c) $t = 235$[ms] (d) $t = 340$[ms]
(e) $t = 415$[ms] (f) $t = 460$[ms]

Fig. 10 A series of photos during an arm motion for grasping a stick-shaped object

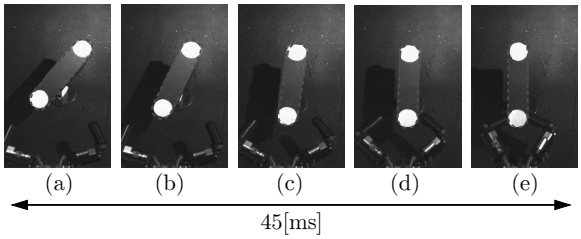
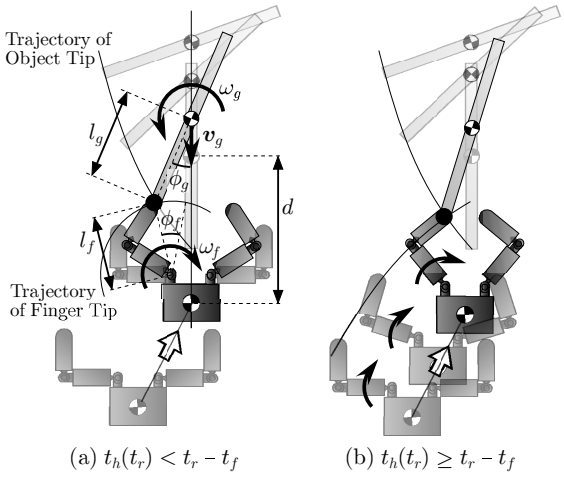


Fig. 11 A series of photos during a finger motion for grasping a stick-shaped object

command is sent from the computer, both fingers start to close (Fig.11(b)-(d)). Finally, both finger can grasp the object successfully, as shown in Fig.10(f) and Fig.11(e).

5. DISCUSSION

In this chapter, we discuss the relationship between the angular velocity ω_f of finger and the velocity of object $(\boldsymbol{v}_g, \omega_g)$, We would once again confirm that each finger starts its closing motion at $t = t_r - t_f$ and completes the motion at $t = t_r$. For simplicity, we neglect the width of each finger and each finger is treated as just a stick without thickness. Also we suppose the case where there is no coupling between the arm motion and finger motion $(t_h(t_r) < t_r - t_f)$, as shown in Fig.12(a). By this assumption, we are released from the complicated motion when they make a collision and allowed to consider only the case where each finger completes its motion at the time $t = t_r$ without any collision with the target object. Fig.12 shows the geometrical relationship between the finger and the object just before making contact with each other, where l_g, l_f, ϕ_g, and ϕ_f are the length between the center of gravity of the object and the tip of the object, the length between the base of finger and the finger tip, and the rotational angle of object between the intersecting point and the goal posture, and the rotational angle of finger between the intersecting point and the goal posture, respectively. In this case, the necessary condition for achieving the procedure explained in the previous chapter is given by



(a) $t_h(t_r) < t_r - t_f$ (b) $t_h(t_r) \geq t_r - t_f$

Fig. 12 Geometrical consideration on capturing a stick-shaped object with rotational velocity

$$\frac{\omega_f}{\omega_g} > \frac{\phi_f}{\phi_g} \tag{20}$$

Ineq.(20) expresses the angular velocity ω_f necessary for achieving the target posture without being disturbed by the object with $(\boldsymbol{v}_g, \omega_g)$. Fig.13 shows the numerical simulation for the relationship between ω_f and $(\boldsymbol{v}_g, \omega_g)$, where ω_f should be inside of the shadowed area under the given data set, $\omega_f^{\max} = 30$[rad/s], $\boldsymbol{v}_g = [0, 0]^T$[mm/s] for the line(a), $\boldsymbol{v}_g = [0, -4200]^T$[mm/s] for the line(b), $\boldsymbol{v}_g = [2100, -3637]^T$[mm/s] for the line(c), $\omega_g^{\max} = 25$[rad/s], $l_g = 75$[mm], $l_f = 96$[mm], and $d = 140$[mm], respectively. From Fig.13, it can be seen that ω_f required the given ω_g on the line(b) increases very little from that of the line(a), while $\|\boldsymbol{v}_g\|$ is equal to that of the line(c). It means that we can pay attention to only the relationship between both rotational velocities if we can choose θ_h satisfying $v_{gx} = 0$. This is because we suppose that the base of hand can move with $\dot{\boldsymbol{p}}_h$ satisfying $t_h(t_r) < t_r - t_f$. In any case, it is important for us to increase the area so that we may have much success rate.

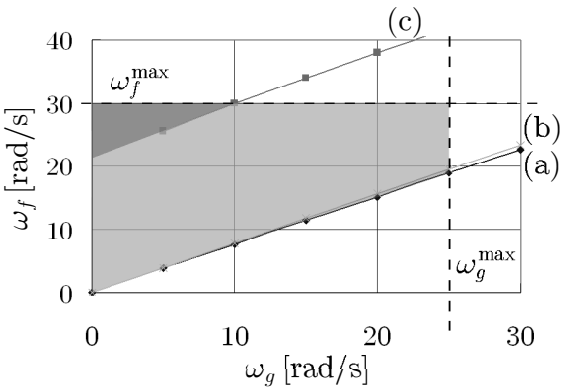


Fig. 13 Relationship between velocities of finger and object

6. CONCLUSION

We discussed the issue on preshaping for capturing the object with rotational velocity as well as translational velocity. We particularly focused on the timing issue for planning the hand motion by linking with the object motion. The main results in this paper is as follows:

(1) Supposing a two dimensional hand, we showed a strategy for determining the time in grasping a moving object geometrically.
(2) The proposed strategy was confirmed experimentally with the assistance of a high speed vision system.
(3) We also considered the necessary condition required for the rotational velocity of finger, and showed the map in connection with the velocity of object.

Acknowledgments

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Walking and Climbing Robot for Locomotion in 3D Environment

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Abstract: One of the traditional problems of the walking robot moving in 3D environment is how to negotiate the boundary of two plain surfaces, which may be convex or concave. In this paper the planning method in the transition region of the boundary is proposed in terms of geometrical view. In each case such as concave and convex, the trajectory that robot moves along has to be determined and the foot positions of the robot associated with the trajectory has to be estimated. The trajectory of the body is derived from the geometrical analysis of the relationship between the robot and the environment. And the position of each foot is estimated by using parameter associated with the hip and the ankle of the robot. The validity of the proposed method is demonstrated through simulations and experiments are performed in the concave and convex environments with limited slope angle.

Keywords: Walking Robot, Quadruped, Slope, MRWALLSPECT

1. INTRODUCTION

Up to now, applications of robots have been continuously discussed in the inspection of industrial utilities such as nuclear plants, oil refinery, chemical plants, buildings, bridges, etc. The tasks for the applications, in general, accompany hazardous working environments as well as difficulties in accessibility. The walking robot can be suggested as one of solutions to cope with these situations and it is required to possess the capability of traveling in three-dimensional environments, different from the general types of walking robots as shown in Fig. 1. Though the environments are composed of primitive geometrical shapes, the robot basically should be able to move such as ground to wall, wall to wall and wall to ceiling, etc. Thus the robot is strongly demanded to walk as well climb on the wall with a special adhesion tools such as suction, magnetic foot etc. and a dedicated gait planning method to move on the environment.

Many researches have been studied on this subject up to now. Hirose et al. have addressed algorithms that generate trajectories of a body and foot positions in the horizontal plain and efficient gait planning algorithm that can be applied to walking on the slope and the wall considering the effect of gravity [1-5]. Shaoping et al. have proposed the algorithm to generate free gait combined with the trajectory of the body in three-dimensional terrain [6-8]. Mohammed et al. have studied a walking algorithm and the mechanism of the robot to walk in the general terrain consisting of horizontal, inclined and vertical plain [9]. Alsalam et al. have studied transition gait from the horizontal plain to the vertical one [10]. Junmin et al. have proposed a transition gait to walk from one slope to another slope and proposed a method of estimation for the turning angle of the body [11][12].

As one of the comprehensive work for the movement in the three-dimensional environment, we propose a gait planning algorithm for the transition movement crossing the slope boundary in this paper. In this work it is addressed how to generate appropriate trajectories of the body for moving on the concave and convex slope, and the method of determining the positions of feet in accordance with the movement of the body. Simulations are carried out for hill with concave and convex boundary to prove the validity of the proposed algorithm and experiment is performed with a wall climbing robot called MRWALLSPECT III [13].

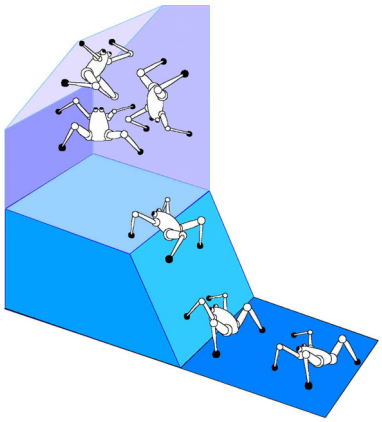

Fig. 1. Navigation in three-dimensional environment

2. MODELS OF ROBOT AND ENVIRONMENT

As depicted in Fig. 2, the leg consists of three links L_1, L_2, L_3 and passive joint ankle with yaw, pitch, roll.

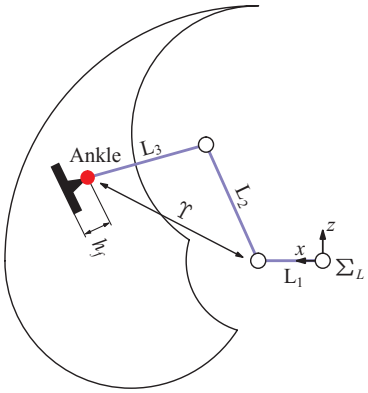

Fig. 2. Leg Structure

The height of foot is h_f and the position of foot is determined by controlling ankle position in Σ_L which is leg frame. Therefore the workspace described in Fig. 2 expresses the area that ankle can reach in zx plain of $\mathbf{S}_L$. The workspace is expressed as

$$(\sqrt{x^2+y^2}-\mathrm{L}_1)^2+z^2=\Upsilon^2 \qquad (1)$$

where **U** is distance between leg joint 2 and ankle and x, y and z are coordinate values of ankle in $\mathbf{S}_L$.

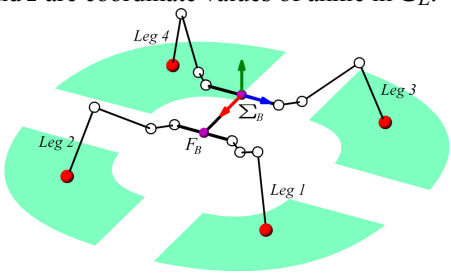

Fig. 3. Robot structure

The Fig. 3 shows robot structure that its frame $\mathbf{S}_B$ which is located in the middle of rear hip joints and the center of front body is F_B. The length of robot body is X_f and the width of front body and rear body is Y_f and Y_r respectively. The pose shown in Fig. 3 is basic form that robot repeats every gait in plain. Two parameters of the basic form, **U** of each leg and the distance h between O_B which is origin of $\mathbf{S}_B$ and plain which ankle is in contact with are utilized as reference values in transition gait. The transformation matrix from $\mathbf{S}_B$ to $\mathbf{S}_{Li}$ (i=1,2,3,4 leg number) is expressed as

$$ {}^{B}_{L1}T=\begin{bmatrix}1&0&0&X_f\\0&1&0&\frac{Y_f}{2}\\0&0&1&0\\0&0&0&1\end{bmatrix} \quad {}^{B}_{L2}T=\begin{bmatrix}1&0&0&X_f\\0&-1&0&-\frac{Y_f}{2}\\0&0&1&0\\0&0&0&1\end{bmatrix} $$

$$ {}^{B}_{L3}T=\begin{bmatrix}-1&0&0&0\\0&1&0&\frac{Y_r}{2}\\0&0&1&0\\0&0&0&1\end{bmatrix} \quad {}^{B}_{L4}T=\begin{bmatrix}-1&0&0&0\\0&-1&0&-\frac{Y_r}{2}\\0&0&1&0\\0&0&0&1\end{bmatrix} \qquad (2)$$

Three-dimensional environment consists of plains which are angled each other. This is slope environment including convex, concave, wall and cliff. To simplify problem, the case that the direction of robot is perpendicular to slope boundary is considered. Let $\mathbf{P}_{1f}$ be first plain that the robot is present in and $\mathbf{P}_{2f}$ be second plain that robot will moves on. In transition gait, $\mathbf{P}_{1f}$ and $\mathbf{P}_{2f}$ are expressed as

$$\Pi_{1f}: x\sin\gamma_1+z\cos\gamma_1=\eta_{1f} \qquad (3)$$

$$\Pi_{2f}: x\sin\gamma_2+z\cos\gamma_2=\eta_{2f} \qquad (4)$$

where $\mathbf{g}_1$ and $\mathbf{g}_2$ are inclined angles of $\mathbf{P}_{1f}$ and $\mathbf{P}_{2f}$ in $\mathbf{S}_B$ respectively, $\mathbf{h}_{1f}$ and $\mathbf{h}_{2f}$ are oriented distance from $\mathbf{S}_B$ to Π_{1f} and Π_{2f} respectively. Π_{1f} and Π_{2f} are plains that the foot of robot contacts directly. As the position of foot is determined by controlling ankle position, the plain that moves parallel by foot height h_f is more useful in gait controlling. Π_1 and Π_2 are the plains that moves parallel by h_f from Π_{1f} and Π_{2f} respectively and expressed as

$$\Pi_1: x\sin\gamma_1+z\cos\gamma_1=\eta_1 \qquad (5)$$

$$\Pi_2: x\sin\gamma_2+z\cos\gamma_2=\eta_2 \qquad (6)$$

where η_1 and η_2 are obtained by adding $\eta_{1f}$and η_{2f} respectively.

3. GAIT ALGORITHM

In transition of slope boundary region, gait planning is constructed with two part. One is determining $\mathbf{S}_N$ which is next $\mathbf{S}_B$ after one gait and the other is determining foot positions. $\mathbf{S}_N$ is obtained by applying t_p to body trajectory and t_p is moving quantity of body. After obtaining $\mathbf{S}_N$, foot positions can be determined by applying **U** of basic form in $\mathbf{S}_N$. In transition of slope boundary region, foot position is not repeated in $\mathbf{S}_B$ after gait, but **U** of each leg is same in $\mathbf{S}_B$ after gait. This gives consistency to gait during transition.

3.1 Body Trajectory and Movement

Body trajectory is classified into two kind of trajectory. One is concave trajectory, the other is convex trajectory. Both concave and convex trajectories are constructed with lines and arc. Lines are determined by applying 0 to *y-axis* value in $\mathbf{P}_{if}$ (i=1,2 plain number) which is moved parallel by h from $\mathbf{P}_{ih}$ along *z-axis* in $\mathbf{S}_B$. $\mathbf{P}_{1h}$ and $\mathbf{P}_{2h}$ are

expressed as

$$\prod_{1h} : x\sin\gamma_1 + z\cos\gamma_1 = \eta_1 + h \quad (7)$$

$$\prod_{2h} : x\sin\gamma_2 + z\cos\gamma_2 = \eta_2 + h \quad (8)$$

The radius of arc is determined by γ, h, d. γ is oriented angle of slope about *y-axis* in $\mathbf{S}_B$ and d is marginal distance between ankle and boundary line of Π_1 and Π_2 when the transition gait is started or completed. The relation of γ_1, γ_2 and γ is follow:

$$\gamma = \gamma_2 - \gamma_1 \quad (9)$$

Eq. (10) and (11) describe radius R of the arc of body trajectory in concave and convex slope respectively. Fig. 4 and Fig. 5 show the body trajectory of concave and convex slope respectively. P_S is the start point of transition gait and P_E is end point of transition gait. The beginning condition of transition gait is the coincidence of F_B and P_S and the completion condition of transition is the coincidence of O_B and P_E.

$$R = \frac{d}{\tan\frac{\gamma}{2}} - h \quad (10)$$

$$R = \frac{d}{\tan\frac{\gamma}{2}} + h \quad (11)$$

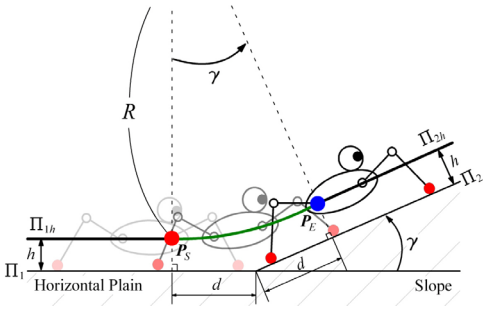

Fig. 4. Body trajectory for concave slope

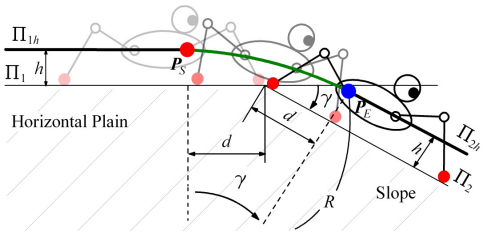

Fig. 5. Body trajectory for convex slope

In concave transition gait, situation is classified into four cases when O_B and F_B moves along body trajectory. As shown in Fig. 6, case **I** is the situation that O_B is on $\mathbf{P}_{1h}$ and F_B is on the arc. The position of O_N which is the origin of $\mathbf{S}_N$ is determined by Eq. (12). If $\| \boldsymbol{P}_S \|$ is less than t_p, P_S is O_N. F_N that is the center of front body in $\mathbf{S}_N$ is determined whether on

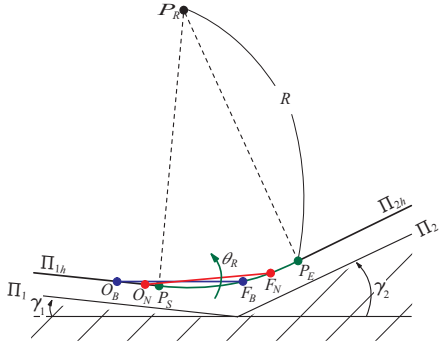

Fig. 6. Case **I** of concave transition

the arc or $\mathbf{P}_{2h}$ by comparing $\| \boldsymbol{P}_E - \boldsymbol{O}_N \|$ with X_f. When $\| \boldsymbol{P}_E - \boldsymbol{O}_N \|$ is bigger than X_f, F_N on the arc is estimated by the condition of Eq. (13) or as shown in case **II** of Fig. 7, F_N on $\mathbf{P}_{2h}$ is estimated by the condition of Eq. (14).

$$\boldsymbol{O}_N = t_p \frac{\boldsymbol{P}_S}{\|\boldsymbol{P}_S\|} \quad (12)$$

$$\begin{aligned} \|\boldsymbol{F}_N - \boldsymbol{P}_R\| &= R \\ \|\boldsymbol{F}_N - \boldsymbol{O}_N\| &= X_f \end{aligned} \quad (13)$$

$$\begin{aligned} \boldsymbol{F}_N \cdot \mathbf{n}_{2h} &= \eta_2 + h \\ \|\boldsymbol{F}_N - \boldsymbol{O}_N\| &= X_f \end{aligned} \quad (14)$$

where $\mathbf{n}_{2h}$ is normal vector of $\mathbf{P}_{2h}$, $\mathbf{n}_{2h} = \begin{bmatrix} \sin\gamma_2 & 0 & \cos\gamma_2 \end{bmatrix}^{\mathrm{T}}$.

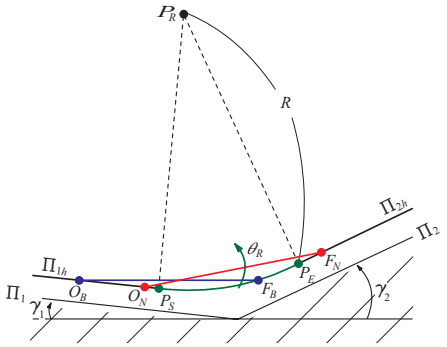

Fig. 7. Case **II** of concave transition

θ_R that is the orientation angle of $\mathbf{S}_N$ is the rotation angle about *y-axis* and estimated by Eq. (15).

$$\theta_R = \operatorname{atan2}((\boldsymbol{F}_N - \boldsymbol{O}_N)\cdot\hat{i},\ (\boldsymbol{F}_N - \boldsymbol{O}_N)\cdot\hat{k}) - \frac{\pi}{2} \quad (15)$$

where $\hat{i} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^{\mathrm{T}}$ and $\hat{k} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^{\mathrm{T}}$

In the case **III** and case **IV**, O_N is determined by being moved from O_B with t_p along the arc. If the arc length from O_B to P_E is less than t_p, O_N is P_E. The position vector $\boldsymbol{O}_N$ is estimated by being rotated from

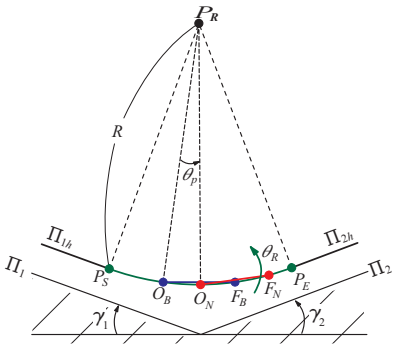

Fig. 9. Case **III** of concave transition

O_B with θ_p of Eq. (16) centering around $\boldsymbol{P}_R$ which is the position vector of P_R. The result is found in Eq. (17).

$$\theta_p = -\frac{t_p}{R} \tag{16}$$

$$\boldsymbol{O}_N = \boldsymbol{P}_R + \boldsymbol{R}_Y(\theta_p)(-\boldsymbol{P}_R) \tag{17}$$

where $\boldsymbol{R}_Y(\theta_p)$ is the rotation matrix about *y-axis*.

As θ_R is equal to θ_p in the case **III**, $\boldsymbol{F}_N$ is estimated by adding $X_f\hat{i}$ rotated by $\boldsymbol{R}_Y(\theta_p)$ to $\boldsymbol{O}_N$ as shown in Eq. (18).

$$\boldsymbol{F}_N = \boldsymbol{O}_N + X_f \cdot \boldsymbol{R}_Y(\theta_p)\hat{i} \tag{18}$$

$$\theta_R = \frac{t_p}{R} \tag{19}$$

where R is of Eq. (11)

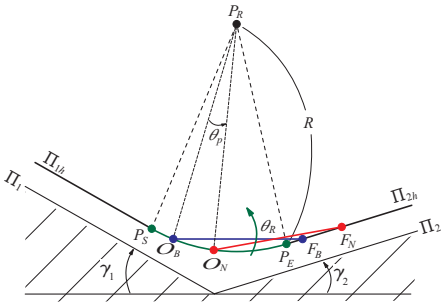

Fig. 10. Case **IV** of concave transition

In the case **IV**, $\boldsymbol{F}_N$ is found in Eq. (14) and θ_R is found in Eq. (15). In the convex transition, the case considered is only one shown in Fig. 10. O_N and F_N are determined by interior division ratio of X_f with $|\gamma_1 - \theta_R|$ and $|\gamma_2 - \theta_R|$. The interior division point P_{T2} is estimated by being moved with t_p along arc from P_{T1} which divides $\overline{O_BF_B}$ with $|\gamma_1|$ and $|\gamma_2|$ ratio interiorly. The position vector $\boldsymbol{P}_{T1}$ is $\left[X_f \frac{\gamma_2}{\gamma} \quad 0 \quad 0\right]^T$ and $\boldsymbol{P}_{T2}$ is estimated by being rotated by θ_R of Eq. (19) from $\boldsymbol{P}_{T1}$ centering around $\boldsymbol{P}_R$ which is the position vector of arc center in Eq. (20). $\boldsymbol{O}_N$ and $\boldsymbol{F}_N$ are found in Eq. (21).

$$\boldsymbol{P}_{T2} = \boldsymbol{P}_R + \boldsymbol{R}_Y(\theta_R)\boldsymbol{P}_{T1} \tag{20}$$

where

$$\boldsymbol{P}_R = \boldsymbol{P}_{T1} - R\hat{k}$$

$$\boldsymbol{O}_N = \boldsymbol{P}_{T2} - \frac{|\gamma_2 - \theta_R|}{\gamma} X_f \cdot \boldsymbol{R}_Y(\theta_R)\ \hat{i}$$

$$\boldsymbol{F}_N = \boldsymbol{O}_N + X_f \cdot \boldsymbol{R}_Y(\theta_R)\ \hat{i} \tag{21}$$

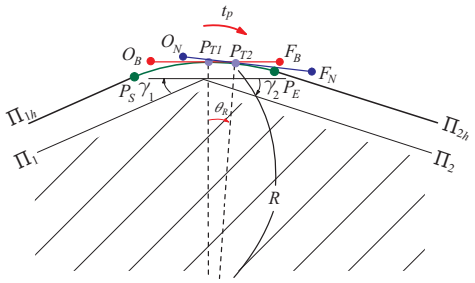

Fig. 11. Case of convex transition

In convex transition gait, the collision between the bottom of robot body and the boundary edge of convex slope must be considered. Let B_t be the distance between *xy* plain of $\mathbf{S}_B$ and the bottom of robot body and h_m be the distance between *xy* plain of robot body and the boundary edge of slope, then it is clear that h_m must be greater than B_t in order to avoid collision. The moment that h_m has minimum value is shown in Fig. 11. In this moment, $|\gamma_1|$ and $|\gamma_2|$ are equal and the workspace of each leg has to have intersected area with $\mathbf{P}_i$ (i=1 to rear legs, i=2 to front legs). h_m is found in Eq. (22) and when h is fixed, the condition is satisfied by adjusting d.

$$h_m = R - \left(\frac{d}{\tan\frac{\gamma}{2}} - h_f\right)\sqrt{1+\frac{d^2}{r^2}} \tag{22}$$

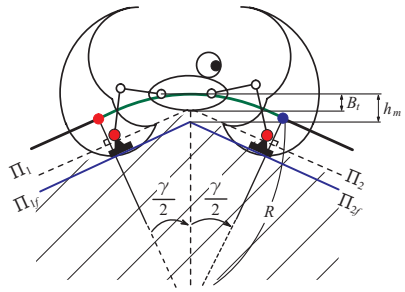

Fig. 12. Collision of convex transition

3.2 Foot Position

The foot position $\boldsymbol{P}$ on waling plain $\mathbf{P}_W$ which is

inclined by γ about *y-axis* in $\mathbf{S}_L$ is determined by applying $\mathbf{U}$ of Fig. 2 in $\mathbf{S}_L$. Let $\mathbf{S}_W$ be the frame whose *xy* plain is coincident with $\mathbf{P}_W$. The origin of $\mathbf{S}_W$ is located from the origin of $\mathbf{S}_L$ by $|\eta_W|\mathbf{n}_W$ and its *y-axis* is parallel with *y-axis* of $\mathbf{S}_L$. Let ${}^W\boldsymbol{P}$ be the description of $\boldsymbol{P}$ in $\mathbf{S}_W$, then the relation of $\boldsymbol{P}$ and ${}^W\boldsymbol{P}$ is described in Eq. (23).

$$\boldsymbol{P} = {}^L_W\boldsymbol{T}\,{}^W\boldsymbol{P} \tag{23}$$

where

$${}^L_W\boldsymbol{T} = \begin{bmatrix} \boldsymbol{R}_Y(\theta_R) & |\eta_W|\mathbf{n}_W \\ 0\ \ 0\ \ 0 & 1 \end{bmatrix}$$

From Eq.~(1), (23) with setting ${}^W z = 0$, we have the workspace area of leg on $\mathbf{S}_W$ and the result is follow

$${}^W x^2 + {}^W y^2 + 2\mathrm{L}_1\sqrt{{}^W x\cos\gamma + \eta_W \sin\gamma} = \Upsilon^2 - \mathrm{L}_1{}^2 - \eta_W{}^2 \tag{24}$$

${}^W\boldsymbol{P}$ is determined by giving ${}^W y$ which is equal to *y* and $\boldsymbol{P}$ is estimated by Eq. (23).

3.3 Synthesis of Body and Foot Position

The foot position $\boldsymbol{P}$ associated with body trajectory is estimated by following steps. First, ${}^N\prod_i$ which is the description of $\mathbf{P}_i$ in $\mathbf{S}_N$ is estimated and transformed to ${}^j\prod_i$ (*i*=1 for *j*=3,4 and *i*=2 for *j*=1,2)which is description of ${}^N\prod_i$ each leg frame in Eq. (2). With applying foot position determination algorithm to ${}^j\prod_i$, ${}^j\boldsymbol{P}_j$, *j*th foot position, is determined in $\mathbf{S}_{Lj}$. By Eq. (2), ${}^N\boldsymbol{P}_j$ is estimated from ${}^j\boldsymbol{P}_j$ and finally $\boldsymbol{P}_j$ is found by transforming ${}^N\boldsymbol{P}_j$ into $\mathbf{S}_B$.

4. SIMULATION

The proposed algorithm is tested by simulation with parameters of MRWALLINSPECT III. The simulation is carried out to two case. One is the going up hill with 35 degree slope and the other is the going down the hill. In both cases, concave and convex transition gait are performed sequentially. Fig. 12 and 13 show concave and convex transition of going up hill respectively. In *Side 3* of Fig. 13, it is observed with attention whether the bottom of robot body collides with boundary edge of $\mathbf{P}_f$ which is displayed as the lower plain. Fig. 14 and 15 show convex and concave transition of going down hill respectively. Needless to say, it is observed with attention whether the bottom of robot body collides with boundary edge of $\mathbf{P}_f$ which is displayed as the lower plain in *Side 3* of Fig. 14. Consequently, the bottom of body and the boundary edge of convex slope are not collide with by applying condition of h_m in Eq. (22).

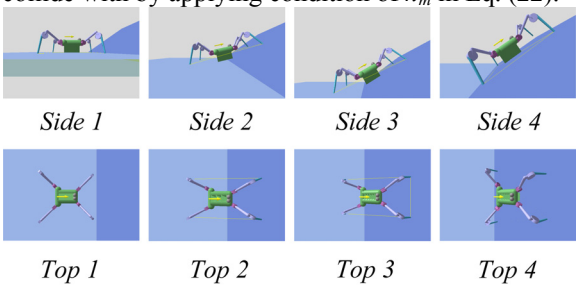

Fig. 12. Go up concave slope

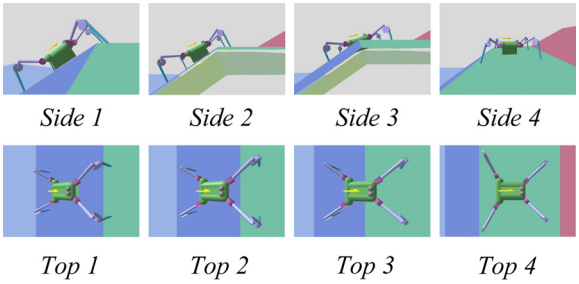

Fig. 13. Go up convex slope

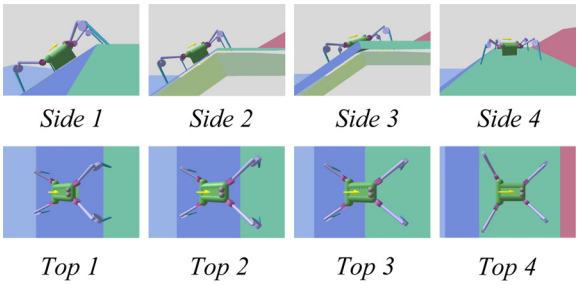

Fig. 14. Go down convex slope

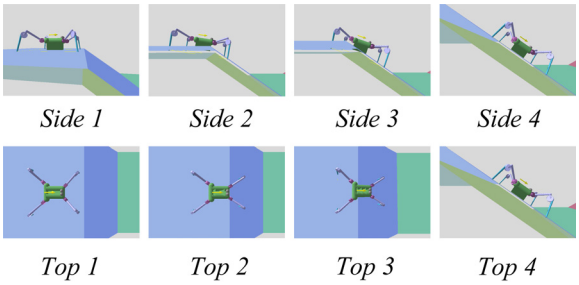

Fig. 15. Go down concave slope

5. EXPERIMENT

In this work, the validity of the proposed algorithms has been demonstrated through some experiments using a walking robot, called MRWALLSPECT III [13]. MRWALLSPECT III had been developed for walking and climbing in three dimensional unstructured environment. The climbing over a slope with concave corner was tested as shown in Fig. 16. When the robot moves up or down on the slope, tumbling of the robot and slipping of the legs should be avoided. However, in the case of the walking robot with suction pads, these problems may be neglected because the legs always have adhesive

forces between the ground and the legs. The *step 1* of Fig. 16 shows the approach process for transition gait in slope environment. In this case, the

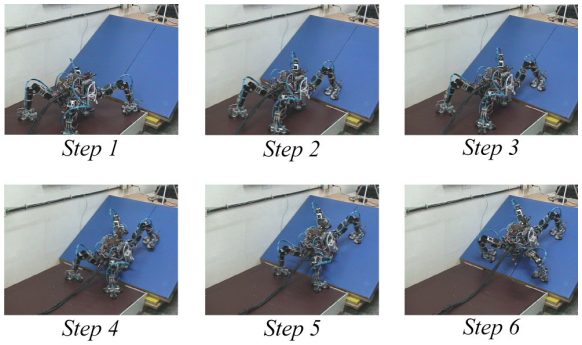

Fig. 16. Concave transition gait in 35 degrees slope

slope angle measured was an approximately 35°. And, the *step 2* and *step 3* are describe the transition in concave corner. In the last step, robot climbs the slope with plain surface using climbing gait.

6. CONCLUSION

In this paper, we proposed the transition gait algorithm for quadruped robot to negotiate boundary region between two plains. First we determine body trajectory in which robot body has to trace and suggest method to determine foot position associated with the body trajectory in terms of robot frame. Also, we explain the possibility condition of convex transition gait. The proposed algorithm is simulated successfully. And the experience with MRWALLSPECT III is tested successfully. The robot movement is smooth during gait. Our next subject is to define robot moving quantity associated with workspace of robot leg.

Acknowledgments

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A Novel Serial/Parallel Pole Climbing/Manipulating Robot: Design, Kinematic Analysis and Workspace Optimization with Genetic Algorithm

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Abstract-This paper introduces an optimized multi-task novel 4 DOF pole climbing/manipulating robot for construction works. The robot can travel along poles with bends, branches and step changes in cross section. It is also able to perform manipulation, repair, testing and maintenance tasks after reaching the target point on the pole. A hybrid serial/parallel mechanism, providing 2 translations and 2 rotations, have been designed as the main part of the mechanism. Optimization of this robot contains workspace optimization of the proposed mechanism and decreasing the total time of reaching the target point, has been established with genetic algorithm method.

Keywords: Design, Optimization, Genetic algorithm, Parallel robots, Pole climbing

1. INTRODUCTION

Climbing robots have received much attention in recent years due to their potential applications in the construction and tall building maintenance, agricultural harvesting, highways and bridge maintenance, shipyard production facilities and etc.
Earlier research in this area has focused on 6-DOF U-P-S (universal prismatic spherical) mechanisms. R Slattern has modeled and simulated a 6-DOF parallel robot with pneumatic actuators. [1]
Later R Aracil et. al. fabricated a parallel robot for autonomous climbing along tubular structures. This robot uses the gough-stewart platform as a climbing robot. Their mechanism also uses 6 cylinders as the grippers (3 cylinders for each gripper) using a total of 12 actuators not counting the actuators needed for the manipulator arm. The robot is able to climb along structures such as trees which are not straight structure [2].
But in recent years some industrial applications such as machine tools has resulted in more attention to parallel mechanisms with less than 6 degrees of freedom. Most of the research in recent years has focused on 3-DOF mechanisms [4, 7, and 8].
While in most applications 3-DOF may be insufficient, complexities and the heavy weight of the 6-DOF mechanisms is also a forbidding factor. As a matter of fact for most pick and place applications at least four-DOF is required (3 translations and 1 rotation to orient the object in its final location) [3]. Also traveling along a pole or tubular structures with bends and branches requires four degrees of freedom (2 translations and 2 rotations along and perpendicular to the tubular axis). These same degrees of freedom are also essential for most manipulation and repair tasks required in the pole climbing applications. Specific examples are fruit harvesting and street/ highway light bulb change operations.
As most of structures made by human being are straight structures with bends and branches, there was a need for less complicated robot for climbing and manipulating along these kinds of structures.
To the best knowledge of the authors, there is no 4-DOF mechanism providing 2 translational and 2 rotational degrees of freedom suitable for such operations. The mechanism proposed in this paper takes advantage of a parallel/serial mechanism providing 2 degrees of translation and 2 degrees of rotation along the desired axes. The mechanism also takes advantage of a novel gripper design, making it suitable for safe pole climbing operations.
Although tasks accomplished by the proposed mechanism, can also be achieved using a 6-DOF Stewart mechanism [1,2], but the resulting mechanism becomes too heavy and complicated for most practical applications. Furthermore using a total of 2 actuators for grippers, the whole mechanism has only 6 actuators.

2. THE ROBOT DESIGN

The proposed pole climbing robot consists of three main parts (Figure1) which are: the 3-DOF planar parallel mechanism, the serial z axis rotating mechanism and the grippers.

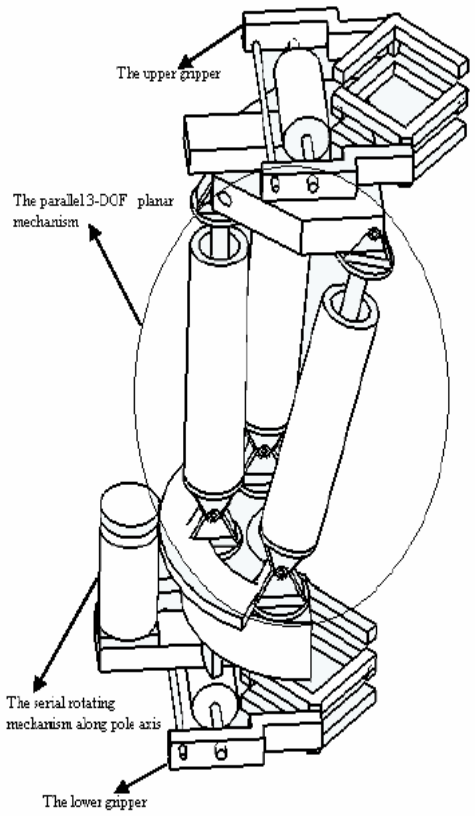

Figure 1. The pole climbing robot model

Combining the 3-DOF planar parallel mechanism with a rotating mechanism around the pole axis provides two rotations and two translations, which is necessary to achieve the design objectives. Furthermore, the linear cylinders used in the parallel manipulator are arranged to encircle the pole and thus reduce the grasp moments on the gripper.
One of the grippers is attached to manipulator, and the other one is attached to the base of the rotating platform. As a result, the grippers have four DOF with respect to each other, allowing for movements along the poles with different cross sections and geometric configurations.
Figure 1 shows the robot model passing the bend section. Using this model we were able to examine the robot possible movements and the robot configurations in order to select the best mechanism and design the mechanical parts. A detail concept of the design and necessarily of these 4 dof has been presented in another paper from the authors [3].

3.1. The 3-DOF planar parallel 3-RPR manipulator

A general planar three-legged platform with three-degree-of freedom consists of a moving platform connected to a fixed base by three simple kinematics chains. Each chain is consists of three independent one DOF joints, one of which is active [4].

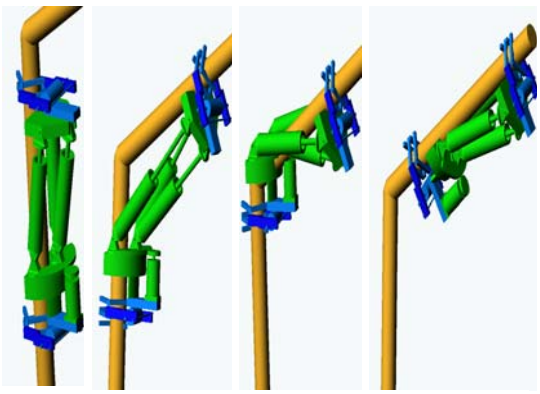

Figure 2. The robot model passing the bend

Since the displacements of the platform are confined to the plane, only R- and P-pairs are used. The possible combinations are therefore: RRR, RPR, RRP, RPP, PRR, PPR, PRP, and PPP. The last combination is excluded because no combination of pure planar translations can produce rotation of the moving platform. Thus, there are seven possible combinations of kinematics chains. These chains can be combined in either symmetric1 or asymmetric groups of three. The active joint in a leg is identified with underline. Since any of three joints, in any of the seven kinematics chain listed, can be actuated here are twenty-one possible leg architectures. On the basis of the following rule which is presented by Merlet [5]: "The chain obtained when locking the actuated joint is not of the PP type" the number of possible leg architectures reduces to eighteen, which are listed in Table 1. Hayes et al. [6] showed that there are 1653 distinct general planar three-legged platforms with three DOF. By neglecting the asymmetric manipulators and eliminating architectures in which the active joint is on the moving platform (these architectures have less rigidity than others), only 12 architectures remain. Since we want to use this mechanism in a hybrid pole climbing robot, the weight of this mechanism is a critical and decisive factor. Mechanisms having two prismatic joints are heavier than others due to the weight of the associated linear guides. The mechanisms with active revolute joints are also heavy because of their transmission systems. As a result, the PRR and RPR architectures are the only viable choice. Finally to minimize the manufacturing costs, the RPR architecture is selected as the more optimal mechanism for this application.

3. KINEMATIC ANALYSIS

The parallel part of the robot hybrid mechanism is a planar parallel robot with 3-R<u>P</u>R chain. The planar parallel 3-R<u>P</u>R manipulator consists of a fixed base plate, a moving platform and three R<u>P</u>R chains that connect these plates. The manipulator with the

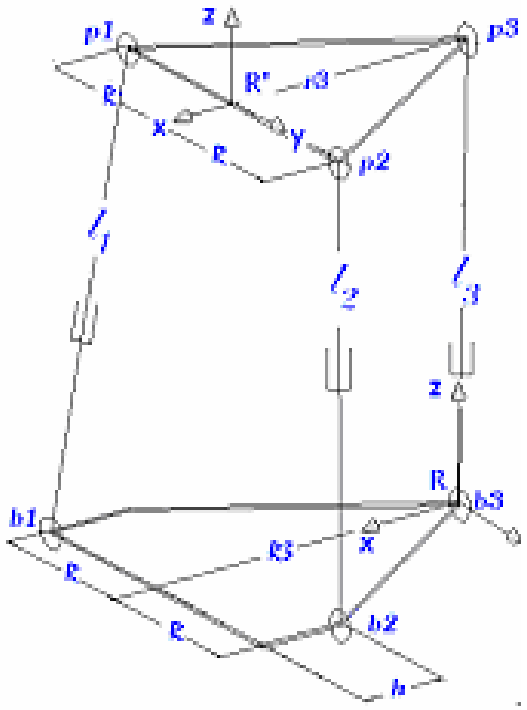

Figure 3. The geometric parameters of the manipulator

relevant geometric parameters is shown in figure 3. Combining the 3-DOF planar parallel mechanism with a rotating mechanism around the pole axis provides two rotations and two translations, which is necessary to achieve the design objectives. The following equations are the result of inverse kinematic analysis of the proposed 3-DOF mechanism.

$$l_1 = \pm\sqrt{(x - R_3)^2 + z^2} \quad (1)$$

$$l_2 = \pm\sqrt{(x - R_3 + h)^2 + z^2} \quad (2)$$

$$l_3 = \pm\sqrt{(x - r_3\cos\theta)^2 + (z + r_3\sin\theta)^2} \quad (3)$$

Since the negative solutions for haven't any geometric interpretation, there are only one inverse kinematics solutions for a given pose of the parallel manipulator (i.e. the positive solutions of (1), (2), (3)).

Using inverse kinematic equations ((1), (2) and (3)), one can obtain following equations as forward kinematic equation of the 3-RPR mechanism.

$$x = \frac{1}{2}\left(\frac{l_2^{\,2} - l_1^{\,2}}{h} - h\right) + R_3 \quad (4)$$

$$z_{1,2} = \pm\sqrt{l_1^{\,2} - \frac{1}{4}\left(\frac{l_2^{\,2} - l_1^{\,2}}{h} - h\right)^2} \quad (5)$$

$$tg\,\theta/2 = \frac{-A \pm \sqrt{A^2 + B^2 - C^2}}{B - C} \quad (6)$$

In which

$$A = 2r_3\sqrt{l_1^{\,2} - \frac{1}{4}\left(\frac{l_2^{\,2} - l_1^{\,2}}{h} - h\right)^2},$$

$$B = r_3\left(\frac{l_2^{\,2} - l_1^{\,2}}{h} + 2R_3 - h\right)$$

$$C = l_3^{\,2} - r_3^{\,2} + \frac{1}{4}\left(\frac{l_2^{\,2} - l_1^{\,2}}{h} - h\right)^2 - l_1^{\,2} - \frac{1}{4}\left(\frac{l_2^{\,2} - l_1^{\,2}}{h} + 2R_3 - h\right)^2$$

Which result in two solutions for forward kinematic equations.

3.1 VELOCITY EQUATION AND JACOBIAN MATRICES

Equations (1), (2) and (3) can be differentiated with respect to time to obtain the velocity equations, which leads to :

$$\dot{x}(x - R_3) + \dot{z}\,z = l_1\dot{l}_1 \quad (7)$$

$$\dot{x}(x - R_3 + h) + \dot{z}\,z = l_2\dot{l}_2 \quad (8)$$

$$\dot{x}(x - r_3\cos\theta) + \dot{z}(z + r_3\sin\theta) + \dot{\theta}\left[r_3(x\sin\theta + z\cos\theta)\right] = l_3\dot{l}_3 \quad (9)$$

Rearranging (7)-(9) leads to an equation of the form:

$$\mathbf{A}\dot{\mathbf{x}} = \mathbf{B}\dot{\boldsymbol{\theta}} \quad (10)$$

And the vector of the input velocities, is defined as

$$\dot{\boldsymbol{\theta}} = \begin{pmatrix} \dot{l}_1 & \dot{l}_2 & \dot{l}_3 \end{pmatrix}^T \quad (11)$$

And matrices ***A*** and ***B***, respectively, the forward and inverse Jacobian matrices for the manipulator are expressed as:

$$\mathbf{A} = \begin{bmatrix} x - R_3 & z & 0 \\ x - R_3 + h & z & 0 \\ x - r_3\cos\theta & z + r_3\sin\theta & r_3(x\sin\theta + z\cos\theta) \end{bmatrix} \quad (12)$$

And

$$\mathbf{B} = \begin{bmatrix} l_1 & 0 & 0 \\ 0 & l_2 & 0 \\ 0 & 0 & l_3 \end{bmatrix} \quad (13)$$

Assuming ***B*** is nonsingular, the Jacobian matrix for the parallel manipulator can be written as

$$\mathbf{J} = \mathbf{B}^{-1}\mathbf{A} \tag{14}$$

Full kinematic analysis of the 4-DOF hybrid mechanism has been presented in another paper from the authors [9].

4. OPTIMIZATION

Even though the most significant optimization in robotic applications is designing the robot with minimum required DOFs, but workspace and path planning optimization can result in using smaller actuators and lower weight of the whole system. As the robot has the ability of doing different construction works with a little change in design, the optimization process should be done with respect to the application. As the workspace area of the robot does not have a close form equation, the best way of optimization of the workspace is using the global search approaches. One of the most efficient methods of global search is genetic algorithm method. Using this method, one can find the best design parameters of the robot, which leads to the optimum system.

Using kinematic equations, some design parameters of the proposed mechanism has been optimized with genetic algorithm method. These parameters include: Lmin, the length of the cylinders at the zero stroke, Lmax, the length of the cylinders at the maximum stroke, R3, r3 and h as it has been shown in figure 3.So the parameters vector will be:
K= [Lmin,Lmax,R3,r3,h].For all objective functions, following parameters have been used for GA algorithm:
Number of generations: 100
Number of individuals in a population: 50
Crossover probability: 0.85
Mutation probability: 0.05

4.1. Genetic algorithm

Genetic algorithms, as powerful and broadly applicable stochastic search and optimization techniques, are perhaps the most widely known types of evolutionary computation methods today. As a matter of fact, genetic algorithm is an optimized global search method.
Genetic operators such as selection, crossover, and mutation are applied to individuals of a population for many generations as the method converges towards the desired solution. A genetic algorithm has the following structure:

Create an initial population.
Repeat the following steps:
Evaluate the fitness of each individual based on an objective function.
Determine the frequency of reproduction of the individuals.
If a probability of crossover is attained, perform a crossover operation (combination of two parents to produce two offspring).
If a probability of mutation is attained, perform a mutation operation (change one of the genes of the chromosome of an individual).
Continue until the maximum number of generations has been attained [10].

Every individual is a possible solution to the problem to be solved. Following above steps, each generation individuals have better fitness value than the previous generations.

4.2 Workspace optimization

The aim of workspace optimization in this problem is not to maximize the reachable workspace of the manipulator. As mentioned earlier optimization process should be done with respect to the application of the robot. Here maximizing the movement of the robot along x-axis is a good objective function. This is due to need for long movements along x direction, for the time that the robot has been received to the target point and need to manipulate along the radial direction of the pole. For this aim, we consider objfun1 in a manner that the program maximizes possible movement along x-direction in constant orientation of the manipulator. This could be done for a specific θ, in which the manipulability of robot along x-axis is important. Here θ depends on the application of the robot. So we have objfun 1=δx

4.2 DEXTERITY OPTIMIZATION:

In some applications optimization of kinematic properties is an important factor. The global dexterity index (GDI) of a manipulator is a measure of its precision over its actual workspace [10].
Gosselin and Angeles defined and computed the GDI based on condition number of the Jacobian matrices [11].One can obtain GDI factor using following equations:
It is well known that the Jacobian matrix is obtained with following equation:

$$J = -B^{-1}A \tag{15}$$

In which A and B is obtained from kinematic equation:

$$A\dot{x} + B\dot{\Psi} = 0 \tag{16}$$

The condition number of the Jacobian matrix J is:

$$k = \|J\|\|J^{-1}\| \tag{17}$$

In which

$$\|J\| = [tr(JWJ^T)]^{1/2} \quad (18)$$

Where W=w**1,** w=1/n, n is the dimension the matrix, **1** is the identity matrix, and "tr" indicates the trace of the matrix.
k may has a value from 1 to ∞.So using ŋ=1/k is a good solution to bound the k value. So ŋ has a value between 0 and 1. ŋ=1 shows a perfect isotropic dexterity and ŋ=0 shows a singular condition. ŋ is a local property of the manipulator and should be integrated over the entire manipulator's workspace in order to get the GDI[10].

GDI=A/B (19)

Where:

$$A = \int_\theta \int_y \int_x (1/k) dx dy d\theta \quad (20)$$

And B is the area of workspace.
If we take constant orientation workspace, the formula will be:

$$A = \int_y \int_x (1/k) dx dy \quad (21)$$

The mechanism with an average dexterity of about 1 has a good dexterity. So objfun2 = GDI.

4.3 Path planning optimization

As mentioned earlier, the robot has the ability of traveling along poles with bends and branches. For the robot, it takes several steps to travel along bends.
Number of these steps depends on the bend angle and the robot workspace. This means that the robot workspace should be optimized due to bends angle of the structure in a manner that the robot can pass the bends with minimum number of steps. For this purpose we should maximize Δz and Δx of the workspace in constant orientation of "θ =180- α" in a way that the equation Δz=tag θ*Δx is satisfied.
In which α is the bend angle and θ is the manipulator angle. Δz is the maximum movement in z direction and Δx is the maximum movement along x direction. The above equation should be satisfied because traveling along bend section of the pole needs a movement of Δz and Δx in which Δz=tag θ*Δx. With larger amount of Δz and Δx in bend angle, the robot can overtake the bend section of the pole with lower number of steps (figures 2&3).So the aim of objfun3 is minimizing the number of steps when the robot is overtaking the bend section of the pole and we consider objfun3=δx in a specific θ with respect to equation: Δz=tag θ*Δx.

5. RESULTS

Above analysis has been done for a typical application of the pole climbing robot. One may use the robot for highways light bulb changing. For this application path planning optimization and optimization of maximum movement along x-direction is considered. Also dexterity optimization has been done for better dynamic properties.
The results have been obtained for a set of typical dimensions. We considered below constraints:

100 mm< Lmin < 300 mm
70 mm< R3 < 400 mm
70 mm< r3 < 400 mm
5 mm< h < R3
1 < α < 5
In which α is Lmax/Lmin.
Then optimization for objfun1, objfun2 and objfun3 has been accomplished and K= [Lmin, Lmax, R3, r3, h] for each objfun has been obtained. (Dimensions are in mm).

The results for objfun1 are:

K= [300 mm, 494.8 mm, 130 mm, 400 mm, 83.3 mm].
In this case dexterity after 10 generation was: 0.2683 and after 100 generation was: 0.2872.

The results for objfun2 are:
K= [300 mm, 1200 mm, 310 mm, 261 mm, 302 mm].
In this case δx after 10 generation was: 2236 mm and after 100 generation was: 2351 mm.
As it was mentioned before, objfun3=δx in a specific θ with respect to equation: Δz=tag θ*Δx.
The GA optimization for objfun3 was performed with bend angle of π/4. It means that θ=π/4.

The results for objfun3 are:
K= [300 mm, 1200mm, 150 mm, 72.7 mm, 140.6 mm].
In this case δx after 10 generation was: 558.6 mm and after 100 generation was: 609.6 mm.
Also objfun4 has been defined as a linear combination of objfun1 and objfun2 and objfun3 it means that:

objfun4= $\alpha_1 w_1$objfun1+ $\alpha_2 w_2$objfun2+ $\alpha_3 w_3$objfun3.

In which w1, w2 and w3 are weight factors and α_1, α_2, and α_3 are factors for mapping all objective functions into one range.
In this example using α_1= 8000, α_2=1 and α_3 =4 and weight factors of w_1=1, w_2=4 and w_3=1 following results has been obtained:

K= [300 mm, 973.2 mm, 190.8 mm, 240.6 mm, 209.6 mm].

6. CONCLUSION

In this paper a solution to autonomous robot pole climbing problem is presented. Some of the advantages of the proposed robotic mechanism over similar fully parallel 6-DOF robots are smaller number of actuators, lighter weight and a less complex mechanism. Also, a unique multi-fingered gripper with the ability to adapt to various poles cross sections and dimensions with only a single actuator is presented. Finally the optimization of the 4-Dof mechanism for a typical application has been studied. Future works include prototyping and control of the proposed pole climbing robot.

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Automation of an excavator based on a 3D CAD model and GPS measurement

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Abstract: This study examines the possibilities of controlling a six degrees of freedom excavator with the final objective of controlling the movements of the excavator by using a CAD model of the road surface. Compared to the traditional excavator with 4 DOF, the excavator was provided with two additional degrees of freedom by applying the 2 DOF Rototilt, an accessory commonly in use. The advantages of automation are faster process of working and less demands on the operator. To study this problem, an Msc.Adams with Matlab/Simulink simulation environment was used.

Keywords: robotic excavator, path generation, dig planning, modeling, simulation, triangular terrain model, CAD

1 INTRODUCTION

A robotic excavator is not a new idea as there are many interesting and advanced systems, for example, Autonomous Truck Loading from Carnegie Mellon University [1], LUCIE from Lancaster University [2] and Komatsu PC05-7 in ACRF [3].
Our studies have focused on 1. heavy use of a modelling environment. 2. an assumption that a CAD model of the target surface is available. 3. a six degrees of freedom excavator compared to the traditional four degrees.
It can be argued that a simulation environment is only used for the lack of money but it does give some advantages such as faster development time, especially, when considering the problem of path generation or checking a set of equations like inverse kinematics.
A road surface CAD model has been used successfully in machine control automation, at least for the road grader [4,5]. The reported speed increase was between 30 - 60%.
Based on the triangular terrain model, the theme in this paper is to derive equations for the bucket position and orientation so that paths L1, L2 and L3 are obtained (see Fig. 5.). We are also interested in defining the kind of information needed about the CAD model and in presenting it.

1.1 Excavator with 6 DOF

The main drawback of a traditional excavator with 4 DOF slightly weakens its possibilities as a robotic excavator, namely the orientation of a bucket's cutting edge is always parallel to y-axel of the coordinate system K_0 (see Fig. 1.) thus limiting the accuracy of bucket control.

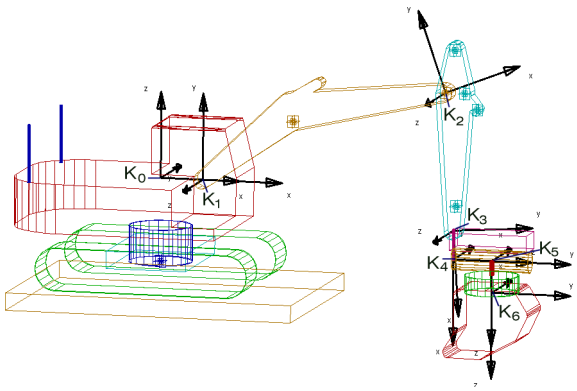

Figure 1. Six coordinate systems attached to an excavator with Rototilt.

So, even if the centre point of a bucket's cutting edge is at the desired location, the corner might travel several tenths of a centimetre misplaced off the target surface. Especially if the yaw angle of an excavator is 45°, displacement is as high as 35 cm for a one-meter-wide bucket.
Rototilt [6] is shown in Figure 2. It is widely used (and well-liked) among excavator operators because it generates two additional degrees of freedom giving more control for the driver to operate. Moreover, the necessity of moving the excavator body is greatly reduced while, for example, digging trenches with a 4 DOF excavator is only possible when the body is located in the same line with the trench. With 6 DOF this can also be done from the side of the line.

Figure 2. Rototilt and demonstration of possibilities of extra two degrees of freedom.

1.2 Short introduction to a 6 DOF excavator model and previous work

Geometry of an excavator is drawn by Adams [7], a program designed to simulate mechanical systems. For control and programming the Matlab/Simulink environment is used. Both products are linked so that the model inside Adams can be controlled from Simulink. This speeds up development work as it is clear that a program specifically designed for implementation of mathematics, is superior in this area and vice versa.

A basic model includes:

1. Analytically solved inverse kinematics for a 6 DOF excavator (Fig. 1.).
2. Positioning and orientation using 2xGPS and an inclinometer (Fig. 3.) so that the transformation matrix T_{SCS}^{MCS} between the SCS (Site Coordinate System) and MCS (Machine Coordinate System) can be calculated.
3. A velocity P-controller to the drive joints to a position calculated by inverse kinematics.

Some more information can be found in the list of references [8, 9].

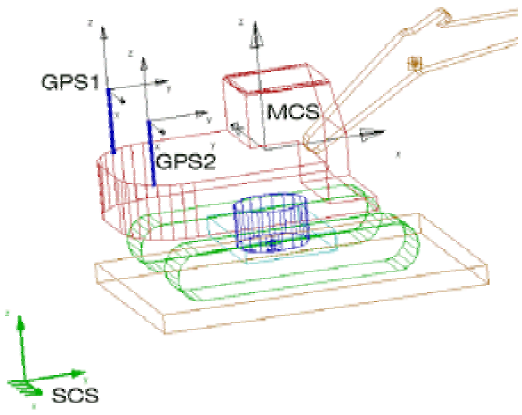

Figure 3. Coordinate systems

2 PATH GENERATION FOR 3D

At the moment the most suitable file format for excavator automation is the triangular terrain model (see Fig. 4. and 8.). Triangles define the plane and are defined by vertices. It is possible to generate a xyz-file, where points defining vertices are written in the text file. This xyz-text-file is the starting point for our study.

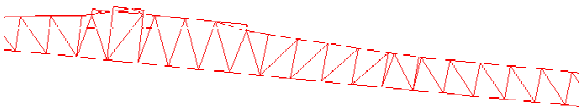

Figure 4. Part of road in a triangular format. Picture taken from MicroStation.

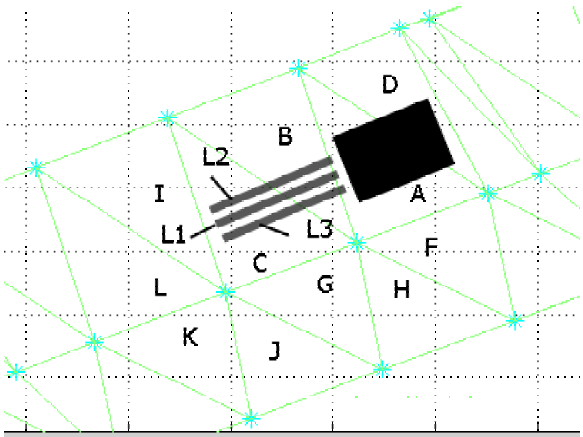

Figure 5. Schematic presentation of an excavator on the triangular surface. L1, L2 and L3 are target paths for the bucket.

2.1 Triangle compilation

As mentioned above, the xyz-format is the base of calculations. The first step is to transform the information to triangles as point information alone is not enough for the purposes of path generation. The Delaunay triangulation [10] was chosen as the method of triangulation because it is included in the Matlab function library.

After triangulation we have a matrix where every row is constructed from three points in a space and a triangle number. The triangle number is called *Tri*.

After joining the triangles together unit normal vector w is calculated by using a cross product for every triangle. Let's denote vertices as $N_1(x_1,y_1,z_1)$, $N_2(x_2,y_2,z_2)$ and $N_3(x_3,y_3,z_3)$ we get:

$$a = \begin{pmatrix} x_2 - x_1 \\ y_2 - y_1 \\ z_2 - z_1 \end{pmatrix} \quad b = \begin{pmatrix} x_3 - x_1 \\ y_3 - y_1 \\ z_3 - z_1 \end{pmatrix} \tag{1}$$

And using a cross product and division:

$$w = \frac{a \times b}{|a \times b|} \tag{2}$$

There are two possible directions for unit normal vector *w* and only one is chosen so that its direction in an SCS is up:

$$\begin{aligned} &\text{IF } w_z \geq 0, \text{ THEN } w = w, \\ &\text{ELSE } w = -w \end{aligned} \tag{3}$$

When considering a large model of a highway with many triangles it is practical to bind shorting parameters for every triangle. A simple solution is to calculate the maximum and minimum distance between the triangle and SCS:

$$\begin{aligned} \text{distmin} &= \min\begin{pmatrix} \sqrt{x_1^2 + y_1^2 + z_1^2} \\ \sqrt{x_2^2 + y_2^2 + z_2^2} \\ \sqrt{x_3^2 + y_3^2 + z_3^2} \end{pmatrix} \\ \text{distmax} &= \min\begin{pmatrix} \sqrt{x_1^2 + y_1^2 + z_1^2} \\ \sqrt{x_2^2 + y_2^2 + z_2^2} \\ \sqrt{x_3^2 + y_3^2 + z_3^2} \end{pmatrix} \end{aligned} \tag{4}$$

When the position of a point is known in an SCS, only the triangles that fulfil the condition - a point can be in a triangle only if the distance of the point is between [distmin, distmax] - can be considered.
The resulting triangle compilation matrix size is *Tri* x 14 and the form is then as follows:

$$\mathbf{tricom}_{Tri,i} = \begin{bmatrix} N_1 & N_3 & N_3 & w & \text{distmin} & \text{distmax} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} \tag{5}$$

2.2 Basic math for triangles, lines and points

Surprisingly simple mathematics is required when working with the L1-3 path generation problem. Two basic problems can be found:
At what point p does a line intersect a plane refined by triangle vertices? This can be solved [11]:

$$\begin{aligned} p &= \frac{-(D + w \cdot N)}{w \cdot N} \\ D &= -(w \cdot N) \end{aligned} \tag{6}$$

Any of the three points can be chosen as *N*. If $w \cdot N = 0$, the line is parallel to the plane.
If a point is on the plane defined by the triangle, does it locate inside the area defined by vertices? Figure 6. presents a situation where point p (x,y,z) is located inside the triangle, defined by the points N_1, N_2 and N_3. In a simulation environment, it is practical to give two local origins which are located at points N_1 and N_2.
By studying Figure 6. it becomes clear that point *p* can be defined as the components of vectors *a*, *b* and *d* (7). In addition, the parameters of those components have to be positive. Only then is the point located inside the triangle.

$$\begin{aligned} t_1 a + t_2 b &= g_1 \\ t_3(-a) + t_4 b &= g_2 \end{aligned} \tag{7}$$

As the point is on the plane, we can discard the z-coordinates. Solving equations (7) yields:

$$\begin{pmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{pmatrix} = \begin{pmatrix} \dfrac{-b_x g_{1y} + g_{1x} b_y}{-a_y b_x + b_y a_x} \\ \dfrac{-a_y g_{1x} + g_{1y} a_x}{-a_y b_x + b_y a_x} \\ \dfrac{-d_y g_{2x} + g_{2y} d_x}{a_x d_y - d_x a_y} \\ \dfrac{a_x g_{2y} - g_{2x} a_y}{a_x d_y - d_x a_y} \end{pmatrix} \tag{8}$$

$$g_1 = \begin{pmatrix} x - x1 \\ y - y1 \\ z - z1 \end{pmatrix} \quad g_2 = \begin{pmatrix} x - x2 \\ y - y2 \\ z - z2 \end{pmatrix} \quad d = \begin{pmatrix} x3 - x2 \\ y3 - y2 \\ z3 - z2 \end{pmatrix}$$

$$a = \begin{pmatrix} x_2 - x_1 \\ y_2 - y_1 \\ z_2 - z_1 \end{pmatrix} \quad b = \begin{pmatrix} x_3 - x_1 \\ y_3 - y_1 \\ z_3 - z_1 \end{pmatrix}$$

And if all $t_i \geq 0$, the point is located inside the area defined by the vertices.

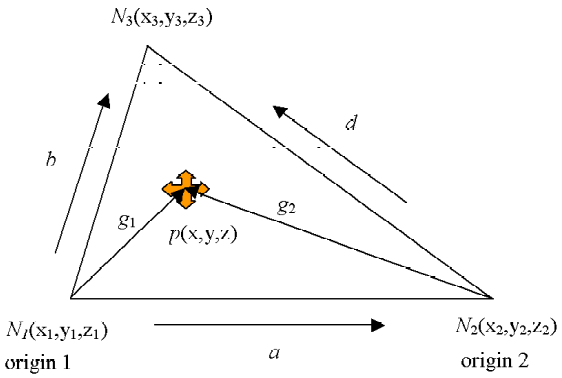

Figure 6. Point *p* inside a triangle

2.3 Identification of triangles on the path in 3D

The next step is to find triangles which are on the path of vectors L1, L2 and L3 (see Fig. 5.). We can remove the z-coordinate information to simplify calculations as the projection to the xy-plane includes all necessary geometric information.

Let's denote the end point of L1 as L1end [x,y,z] and we chose the direction of L1 in the following way:

$$x_{proj} = T_{SCS}^{MCS}\,[1..2,1] \tag{9}$$

This is not a totally accurate way, but if the excavator is close to the target plane and the reach is approximated as a sphere, it gives a close enough approximation for an initial study.
For the L1end we then get:

$$\text{L1end}[x,y] = O_{\text{MCS}}[1..2] + \text{distmaxL1}\cdot x_{\text{proj}} \tag{10}$$

, where $O_{\text{MCS}}[1..2]$ is the MCS origin in an SCS, and distminL1 is a system-specific parameter giving the maximum reach of an excavator, similarly distminL1 is defined as the minimum reach. For the complete vector L1 we can then write a discrete function:

$$\text{L1part}[x,y]_n = \text{L1end}[x,y] - n/\text{kmax} \cdot (\text{distmaxL1-pitminL1})\cdot x_{\text{proj}} \tag{11}$$

, where n = [1,2,3.. kmax] and kmax is the number of samples and gives a resolution for triangle change. Especially when n = kmax the starting point of L1 is acquired.
The procedure is the same for L2 and L3, only L2end[x,y] and L3end[x,y] points are calculated a bit differently by using the width parameter klev. It should be noticed that klev is given in 2D, and thus in 3D the distance might vary.

$$\begin{aligned} \text{L2end}[x,y] &= \text{L1end}[x,y] - \text{klev}\cdot ty \\ \text{L3end}[x,y] &= \text{L1end}[x,y] + \text{klev}\cdot ty \\ ty &= \frac{T_{SCS}^{MCS}\,[1..2,2]}{\left|T_{SCS}^{MCS}\,[1..2,2]\right|} \end{aligned} \tag{12}$$

The next step is to find triangles by using equations (8) and then reduce all unnecessary data points. An example of the resulting group is given in Figure 7. One can see how the points are chosen at the end and the start of the path, and between them only when the triangle changes.
After specifying the path matrix in 2D it is transformed to 3D by using the normal vector *w*, which was created at the triangle compilation stage. One form of equation for the plane is:

$$\begin{pmatrix} w_x \\ w_y \\ w_z \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} - \begin{pmatrix} w_x \\ w_y \\ w_z \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = 0 \tag{13}$$

Which is solved for z:

$$z = \frac{-1}{w_z}\left(w_x x + w_y y - \begin{pmatrix} w_x \\ w_y \\ w_z \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} \right) \tag{14}$$

A data set for the path point matrix in 3D is illustrated in Figure 8. The same set is in Figure 7

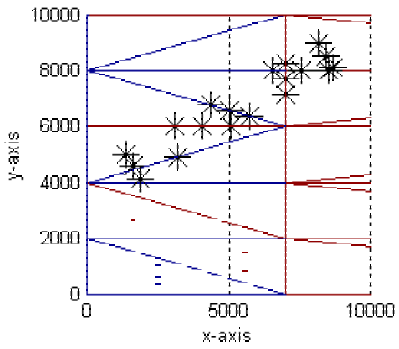

Figure 7. Points defining L1, L2 and L3 on 2D triangle surface.

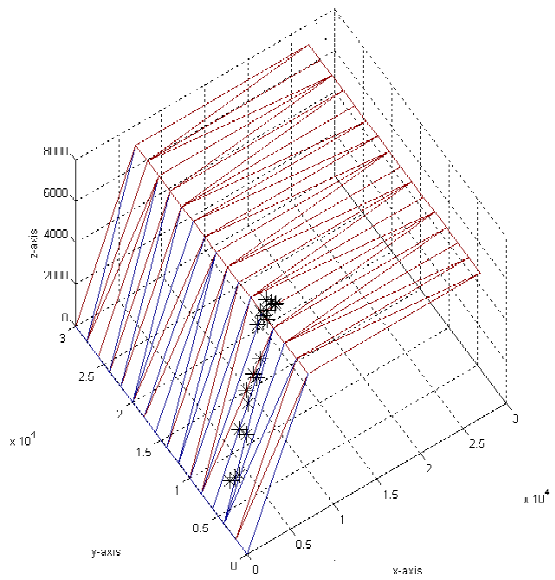

Figure 8. Points defining L1, L2 and L3 on 3D triangle surface. Data set is the same as in Figure 5.

2.4 Path and orientation of a bucket

In a previous study of a 6 DOF excavator, inverse kinematics was created to bind the K_0 and K_6 coordinate systems (see Fig. 1.) and the bucket was left out of the study. The reason for this was mainly that the bucket shape and size could vary a lot, and that it is still unclear what the best position and orientation for K_7 is. So, we need to create a transformation matrix from the bucket tip to K_6. Matrix (15) and Figure 9.

$$A_7^6 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & LV \\ 0 & 0 & 1 & -LK \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (15)$$

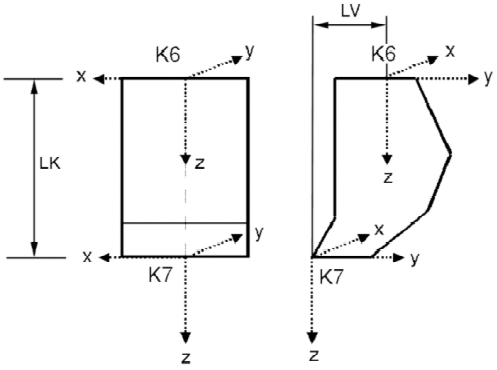

Figure 9 Coordinate systems K_6 and K_7

To simplify the creation of path vectors, a control matrix is defined by using points the created in section 3.3. Format is:

$$\mathbf{pathcont} = \begin{bmatrix} Tri & x & y & z \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix} \quad (16)$$

As one can see, the first column keeps the triangle number, so we can use **tricom** matrix (5) to read specific information from triangles. The last three columns define the points illustrated in Fig. 8. The path is then defined:

$$pathvec_i = \mathbf{pathcon}[i,2..4] + s \cdot \left(\frac{\mathbf{pathcont}[i+1,2..4] - \mathbf{pathcont}[i,2..4]}{\left| \mathbf{pathcont}[i+1,2..4] - \mathbf{pathcont}[i,2..4] \right|} \right) \quad (17)$$

Parameters (above) can be expressed as a function of time so that $s = \text{velocity} \cdot \text{time}$. In this way the constant speed for bucket movements is achieved. For index i, a triangle change, we get a simple condition:

$$s < \left| \mathbf{pathcont}[i+1,2..4] - \mathbf{pathcont}[i,2..4] \right| \quad (18)$$

Orientation of a bucket is easily obtained from the calculation above. Let us name the transformation matrix, which defines orientation and position of a bucket in an SCS as T_{SCS}^7. By examining Figure 1. it is clear that the z-axis of the K_7 coordinate system has to be in the opposite direction of the triangle normal vector *w.* Thus we get:

$$T_{SCS}^7[1..3,3] = -w \quad (19)$$

Logically (see Fig. 1) we can see that the direction of the y-axel should point away from the excavator. More exactly its direction should be opposite to *pathvec*:

$$T_{SCS}^7[1..3,2] = -\frac{pathvec_i}{\left| pathvec_i \right|} \quad (20)$$

We know about the x-axel that it is on the plane defined by the triangle (as is y-axel) and its direction is obtained by using a cross product:

$$T_{SCS}^7[1..3,1] = \frac{T_{SCS}^7[1..3,2] \times T_{SCS}^7[1..3,3]}{\left| T_{SCS}^7[1..3,2] \times T_{SCS}^7[1..3,3] \right|} \quad (21)$$

The transformation matrix T_{SCS}^7 defining the desired bucket position and orientation in an SCS is established.

3 CONCLUSION

It was show hot it is possible to use CAD reference for bucket positioning. Triangular terrain model was first compiled to xyz-file format and from there it was derived equations to formulate target transformation matrix T_{SCS}^7 for purposes of excavation bucket control.
Combining this result with a transformation matrix T_{SCS}^{MCS}, which in our model was created by using 2xGPS and a inclinometer, it is possible to form set points for bucket in 3D and in case of 6 DOF excavator also orientation is defined.
Also for further use a form of matrices defining target points **pathcont** and information gathered from triangles **tricom** is found to be efficient.

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IDENTIFICATION OF PARTIALLY-EXPOSED METAL OBJECT

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Abstract: This paper describes a method of automated type and pose (position and orientation) identification of partially exposed metal objects that makes excavation of hazardous materials safe and efficient. The object pose is estimated by matching a model of the object to the area that is extracted from the range image using the characteristics of metal objects. Experimental results show feasibility of type and pose identification of partially exposed objects.

Keywords: Automated Excavation, Vision System, Pose Identification, 3-D Data Analysis, Recognition of Object, Abandoned Munitions, Range Image.

1 INTRODUCTION

It is desired that removal of hazardous materials such as abandoned chemical weapons from burial pits should be completed safely in a short span of time. It is required to excavate metal objects safely and efficiently. Safe and quick excavation tasks make progress of plan of safe environment recovery projects [1-4].

In order to excavate metal objects, workers remove soil around the objects so that they identify the object shapes. According to the condition of the soil around the objects, and the pose of the objects, it takes large cost for removing the soil until the workers can identify the object shapes.

We have proposed an automated excavation system to excavate the metal objects quickly and safely [2]. To achieve the excavation task, the system removes soil around the metal objects safely and quickly at first. Next, the system identifies type and pose (position and orientation) of the metal object. After the identification, the manipulator excavates the metal object. Several metal objects are exposed partially since the soil around the objects and the other objects hide a part of the objects. Therefore, it is required to estimate the pose and type of the metal object by measuring hidden part of the object using a vision sensor and a metal finder.

This paper describes a method of automated pose identification of partially exposed metal objects in order to excavate hazardous materials safely and efficiently. This method extracts areas of the several objects from the captured three-dimensional range image. Type and pose of the metal object are determined by the matching the target area to the reference shape model of the object given beforehand.

This paper focuses on the pose estimation algorithm based on three-dimensional pattern matching in excavation and recovery system. Pose accuracy of the object influences the width of the area for scanning a hidden part of the object with a metal finder. This width of scanning area influences efficiency of the excavation task.

We have carried out the measurement of the object pose under the several conditions of the target object. Experimental results show feasibility of the type and pose identification of the partially exposed object.

2 SYSTEMS OVERVIEW

We introduce an overview of the automated excavation and recovery system. Buried metal objects have several characteristics shown as follows:

(1) The types of metal objects are several since an object is mass-product materials.
(2) Color of the object has changed for the long term by the corrosion and rust.
(3) Objects has deformed because of the corruption and the rust of the surface of the object.

These facts enable the automated identification and excavation system. From the characteristics (1), the automated pattern matching method is useful for identification of the type and pose of the metal object.

From the characteristics (2) and (3), it is difficult to use the color data and precise shape data for identification. In addition, color data is not useful

for this automated excavation system, since the change of light source influences this data strongly.

We use range data captured by a three-eye camera or a laser range finder for the data capture system of the automated excavation and recovery system. Figure 1 shows the overview of automated excavation system. The type and pose of the metal object are estimated using the three-eye camera. The robot arm manipulates and recovers the metal object using the sensory data. If the computer cannot determine orientation of the metal object since the area of the exposed object is small, the computer obtains the orientation data using the scanning around the candidates of the object pose by the metal finder. Then the manipulator removes the soil around the metal object.

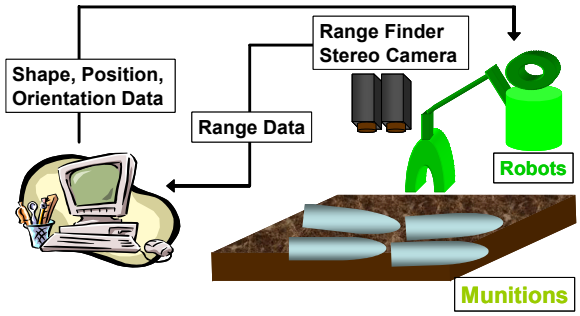

Figure 1: Systems overview.

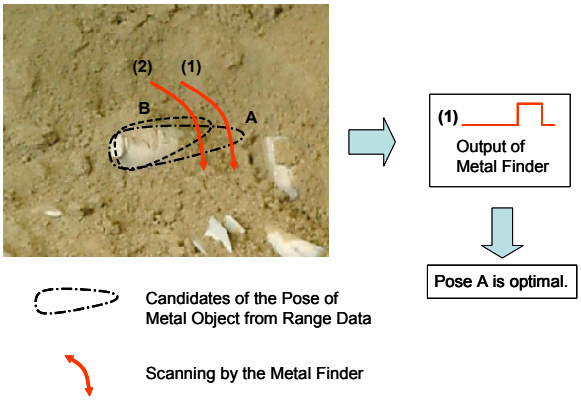

Figure 2: Pose estimation of metal objects using metal finder.

Figure 2 shows an example of pose estimation of a buried object that is exposed partially. The pose of buried object is ambiguous since the range sensor measures the data of only the exposed area. Thus, we obtain a precise pose of the object by searching for the buried part of the object using a metal finder.

We explain a method of the decision of the pose of the partially exposed object using a metal finder. The shapes expressed by the dashed line A and B in figure 2 are candidates of the pose of the metal object from the range data. The pose and type of the metal object is determined by the models of the metal object and the scanning data by the metal finder ((1) and (2) in figure 2). Since the metal finder replies on the trajectory (1), we consider that the candidate (A) is more suitable for the object pose.

In order to discuss the accuracy of the pose estimation of the object, we use only the range data captured by the three-eye camera in this paper. The width of the search area by the metal finder is decided by the pose accuracy of the object by the range data.

3 AUTOMATED IDENTIFICATION OF PARTIALLY EXPOSED METAL OBJECT

We describe a procedure of the automated identification of type and pose of a metal object using a three-eye camera system. The camera captures data about the metal object exposed partially and makes a range image of the exposed area of the object from the captured data. The computer estimates and detects a part of the target object using the range image data. The type and pose of the metal object are determined by the matching to the reference shape model of the object given beforehand. The procedure of this process is shown as follows:

(1) Obtain a range image data using the three-eye camera.
(2) Detect the area of the target object from the range data.
(3) Approximate the axis of the target object by the linear fitting by the least-squares method.
(4) Obtain the range data on the plural planes that are perpendicular to the approximated axis of the target object.
(5) Fit an ellipse to the range data on each plane, and estimate the axis of the target object using the center of the ellipses.
(6) Match the range image to the model of the target object along the estimated axis of the object. The position that is matched to the model the best regards as the estimated position of the target object.

4 EXPERIMENTAL CONDITIONS AND POSE IDENTIFICATION ALGORITHM

We explain the experimental condition of the pose identification of the metal object and pose identification algorithm. The detailed algorithm of pose identification is described using a part of the experimental result.

4.1 Experimental Setup

Figure 3 shows the experimental setup in our laboratory. Three-eye camera are fixed 700 [mm] above the target area vertically. The camera directs to the target area. We use Digiclops (focal range f = 3.8 [mm], the range of capturing is more than about 50 [cm]) as the three-eye camera. The distance to the

target area is obtained by the triangulation based on the stereo vision. The distance can be measured in the area that the view of at least two cameras are overlapped. The size of the image data for range image is 640×480 [pixels] and the distance is obtained by each pixel. The matching between the image pixels of each camera is obtained by correlation between the masks centering on the target pixel defined beforehand. The correlation is obtained based on the Sum of Absolute Difference (SAD) matching method. The size of the SAD mask is 15×15 [pixels].

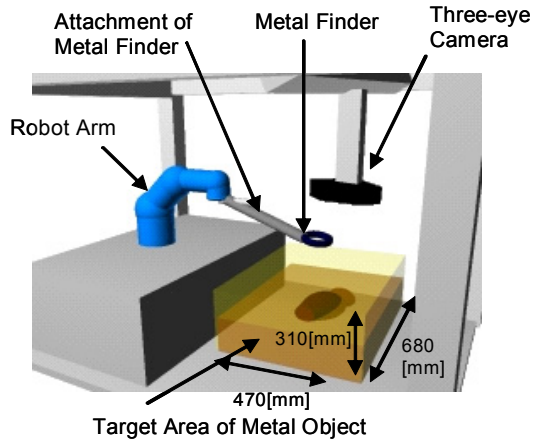

Figure 3: Experimental setup.

4.2 Obtain range image of target area

Figure 4 shows the image data and range image data captured by the three-eye camera. The range image data near a center is used in order to exclude the data of the container. The range data are transposed to the two-dimensional image. The light pixel indicates the near point, and the dark one indicates the far point. The image is called range image. The gradation of one degree of the range image indicates 1[mm]. The black pixel indicates that the distance of the pixel cannot be obtained. Figure 5 shows the image data of the target area that is plotted in three-dimensional volume. The white line of the figure 5 indicates the horizontal and vertical axis of the camera. An intersection of these lines indicates the center of the area of view.

4.3 Extraction of metal object area

The computer extracts the area of the metal object from the obtained image data. The area of the metal object is extracted from the range image using the dynamical threshold based on the watersheds algorithm [5].

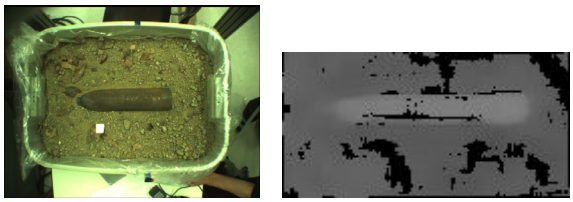

Figure 4 : Image and range data of the target area.

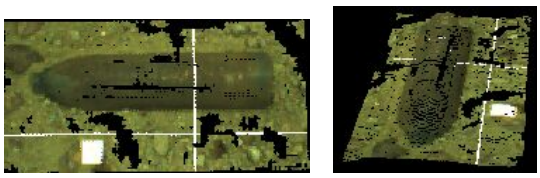

Figure 5 : Range Image (3-D volume).

The extraction process consists of the selection of the candidate of the metal objects and the segmentation of the range image based on the watersheds algorithm. The set of initial points of the candidates of the metal objects is selected from the histogram of the range image. The computer segments the range image into several areas of the metal object.

(1) Selection of the points that the target objects exist (initial points)

This process selects the candidates of the object areas from the histogram of range image and the labeled range image. The precisely procedure of the selection of the candidates of the target objects (initial points of the watersheds algorithm) is shown as follows:

1. Make a histogram about the distance from the range image.
2. The threshold of the range image is calculated from the histogram. The threshold extracts the domain of 20[%] of nearer ranks from the camera.
3. The range image is transferred to a binary image using the threshold. The binary range image is labeled. The large label, whose area is more than 150 [pixels], is considered as a target object. The centers of the gravities of the target objects are calculated.

These gravities are used as the set of the initial points of the watersheds algorithm.

(2) Area detection based on watersheds algorithm

Watersheds algorithm is a method of the segmentation of the image data. In this method, the brightness of the pixels regards as the altitude, and the image data regards as the geographical feature. Water is poured into positions with low altitudes, and the geographical feature is divided bordering on the watershed that divides a basin. This method divides the image data into the several areas such as the division of the watersheds. In this experiment, the set of the candidates obtained the procedure (1) is used as the initial points of each divided area. We apply the expansion task of the divided area from the initial point to the segmentation procedure. The precise

procedure of this watersheds algorithm is shown as follows:

1. The set of the centers of the gravities obtained procedure (1) is the initial points of the algorithm. The brightness of the pixel of the initial point is the initial level of the water.
2. Search for the eight-neighborhood of the pixel that belongs to the object area (x, y). The initial direction of the search process is rightward in the movement from the past position of the basis of search to the present position. The search direction is clockwise. If there is a point whose brightness (water level) is lower in the eight-neighborhood, the new position (x, y) of initial point is set the position (x', y') of the pixel whose brightness is the lowest, and the process 2 repeats recursively. If not, goes to process 3.
3. The amount of the increases of the area of the target object when a water level is gone up is calculated. If the amount of the increases is smaller than the threshold (1300), water level (base brightness) is gone up, and goes to process 2. If the amount is larger than the threshold, the expansion process is ended.

The area belong to the area that is obtained through this process is the object area, and the other area of the image is the background image. Through this method, we obtain the binary image of the object area. After smoothing and labeling of the binary image, the binary image are filtered about the area of the target object (threshold is that the area is more than 150). The each filtered label is considered as the area of the target objects. The extracted target object is shown in Figure 6. The range image referred to the area of the target object is shown in Figure 7.

Figure 6: Extracted target object.

Figure 7: Range image of the target object.

4.4 Estimation of axis of the object

This process estimates the rotary axis of the target object from the partially object shape. The form of the target object is approximated with a body of revolution and the rotary axis of the object is estimated from the three-dimensional shape of the object area. The target object is rotary symmetrical, and the axis of the object is called principal axis.

First, as the approximated axis of the target object, the inertial axis of the range data of the target object is calculated. Figure 8 shows the approximated principal axis on the range data.

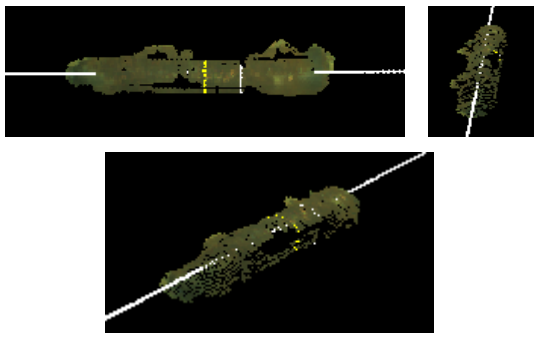

Figure 8: Approximated axis of the object.

Next, we suppose the several planes that are perpendicular to the approximated axis of the target object. We suppose that the range data on each plane are the data obtained from the surface of the target object, and fit the ellipse to the data set on the plane. In the experiment, the range data that are neighborhood of the plane consider as the range data on the plane. The fitting algorithm is conic fitting method developed by Kanatani [6]. If the result of conic fitting to the data on the plane is not an ellipse, the fitting result is not used.

Figure 9 shows the result of conic fitting to a set of the range data on a plane. The origin of the figure indicates the approximated principal axis of the object. The pixels illustrated by the circle indicate the range data of the object. The estimated center of the ellipse indicates the square in the figure.

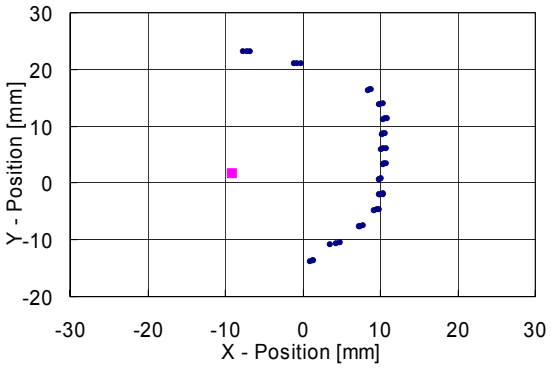

Figure 9: Estimation of center of ellipse.

The set of the range data on the perpendicular plane to the center axis for the ellipse fitting, the computer selects the range data to improve the accuracy. We suppose a circle whose center is the point that is nearest to the camera, and the radius of the circle is that of the target object. The range data that are in the circle are selected. The inertial axis of the center of the ellipse obtained by the plural planes is calculated, and we suppose the principal axis of the target object. Figure 10 shows the principal axis of the object. We set the perpendicular planes by 8 [mm].

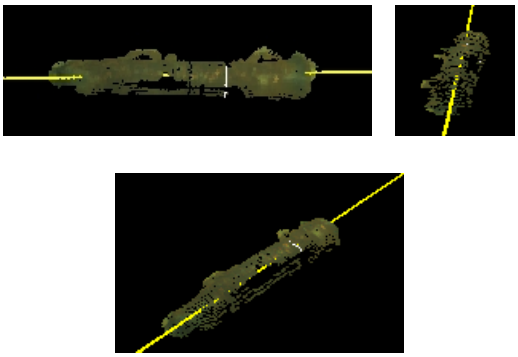

Figure 10: Principal axis of the target object.

4.5 Object matching along the principal axis

This process matches the model of the object to the range image along the estimated principal axis of the target object. The distance between the model and the range image data is calculated. The distance between the model data and image data is calculated about each displacement along the principal axis of the target object. The displacement that the distance between the model and the range image is minimum value is the estimated displacement along the principal axis of the object. Therefore, the position of the target object is obtained. Figure 11 shows the pose estimation result of the target object. The white dots indicate the fitting result of the target model to the range image data.

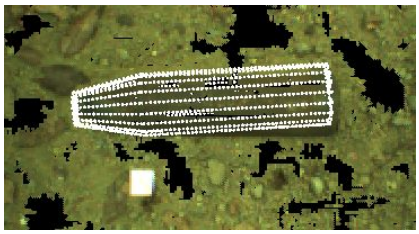

Figure 11: Pose estimation result.

5 EXPERIMENTAL CONDITIONS

We carry out the pose estimation experiment under several conditions about types and poses. The experiment conditions are type, ratio of the exposed area, depth of the object, and relationship of between two objects.

(1) Ratio of the exposed area of the target object

The ratio of the exposed area of the target object are defined as the area ratio of the model projected to the X-Y plane shown in Figure 12. This ratio of the exposed area is 1 if the object is on the plane.

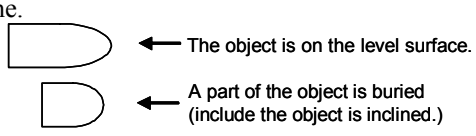

Figure 12: Ratio of the exposed object area.

(2) Depth of the object position

The depth of the target object is compared in the case the target object is exposed partially. In partial buried case, the depth of the lowest point of the object as shown in Figure 13(a), and the depth of the highest and lowest point of the object as shown in Figure 13(b). Since the metal finder is not used in this experiment, the pose estimation of the perfectly buried object is not carried out.

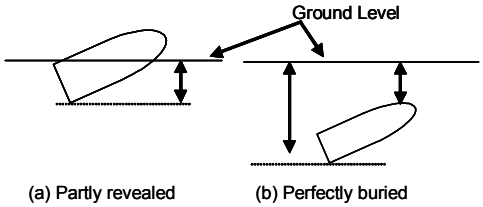

Figure 13: Depth of the object position.

(3) Type of the target object

The type of the target object is 75[mm] and 90[mm] object.

(4) Vertical orientation of the object

The vertical orientation is defined as the angle about the horizontal direction. In this experiment, the conditions of the vertical orientation are set 0, 30, 60, and 90 [deg].

(5) Position of the neighborhood objects

The number of the neighborhood object is one. The relative relationships between each object are defined three parameters d, , and h shown in Figure 14 and 15.

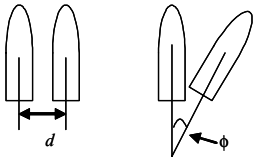

Figure 14: Relationship of between two objects in horizontal plane.

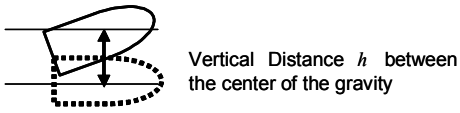

Figure 15: Relationship of between two objects in vertical plane.

6 EXPERIMENTAL RESULTS

We have estimated pose of the metal object under several conditions of the object shown in Figure 16. Experiment Condition are shown as follows: (1) θ= 0 [deg], exposed rate about object area: 100[%]. (2) θ = 0[deg], exposed rate 70[%]. (3) θ = 30[deg], exposed rate 50[%]. (4) θ = 30[deg], exposed rate 40 [%]. (5) θ= 60 [deg], exposed rate 50[%]. (6) θ = 90[deg], exposed rate 20[%], (7) Horizontal rotation between

two objects. ϕ = 0 [deg], both θ = 0 [deg], exposed rate 100[%]. (8). ϕ = 30[deg], θ = 0[deg], exposed rate 100[%]. (9) Objects are set vertically. Upper object: θ= 30[%], exposed rate 50[%].

The estimation result is shown in Table 1. In the case of (4) and (6), the principal axis of the object is not obtained. From the table, when the target object is horizontally oriented, we obtain the object pose accurately. On the other hand, the object is inclined in some extent, the axis is estimated inaccurately, and then no accurate model matching can be achieved.

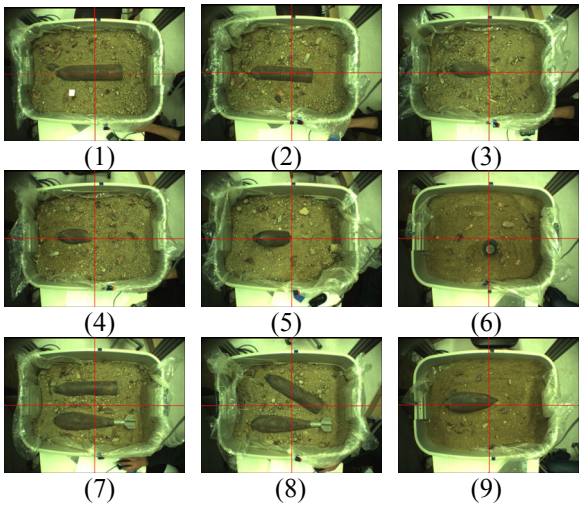

Figure 16: Experimental condition.

Table 1: Experimental result of pose estimation.

Experiment Condition	Position Error [mm]			Orientation Error [deg]	
	x	y	z	ϕ	θ
(1)	-0.5	-12.8	-11.2	-3.5	2.0
(2)	2.4	-20.9	-18.0	4.2	2.0
(3)	40.4	17.5	-125.8	4.4	-30.0
(5)	-58.7	-36.5	-175.1	-11.1	-38.3
(7)	45.4	9.0	-22.6	2.6	-0.4
	28.8	19.7	-30.0	4.7	-1.1
(8)	4.2	-0.6	-5.5	1.6	2.1
	20.4	37.7	-28.2	7.6	-1.1
(9)	90.9	-24.7	-62.7	-5.3	-18.2

From this result, the error of the direction of the orientation is large, in the case the object inclines about the horizontal plane along the vertical axis. Failure of ellipse fitting of the range data to the perpendicular plane about the initial rotary axis is one of the reasons of the error of the object. On the other hand, if the objects are on the level surface and the object is exposed highly, the pose of the metal object estimates accurately using our proposed method. It is expected that the object pose be estimated accurately since the principal axis of the object are estimated more accurately.

The value of evaluation function of matching to the model approximated to the pillar does not change, since the model of the object is matched to the range data. It is useful to use of the end of the model is applicable to the pose identification to solve this problem.

7 CONCLUSIONS

This paper describes an automated identification method of type and pose of partially exposed metal objects based on the range image data. Experimental results show feasibility of the type and pose identification of the partially exposed object. Object orientation about the horizontal axis is inaccurate. We show that the object pose are accurate if the principal axis of the target objects is estimated with high accuracy.

The evaluation of type identification is future work. The estimated pose of the object has to be more accurate in order to apply the practical excavation task.

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PROPORTIONAL-INTEGRAL-PLUS (PIP) GAIN SCHEDULING CONTROL OF AN INTELLIGENT EXCAVATOR

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Abstract: This paper considers the design and implementation of an electro-hydraulic control system for a robotic excavator, namely the Lancaster University Computerised and Intelligent Excavator (LUCIE). The excavator is being developed to autonomously dig trenches without human intervention. Here, a gain scheduling design, based on Proportional-Integral-Plus (PIP) control methods, is utilised to regulate the highly nonlinear joint dynamics. Simulation and initial field tests both demonstrate the feasibility of the proposed technique, with the excavator arm directed along specified trajectories in a smooth, fast and accurate manner.

Keywords: robotic excavator; model-based control; gain scheduling control; proportional-integral-plus.

1. INTRODUCTION

The civil and construction industries currently deploy a large number of manually controlled plants for a wide variety of tasks within the construction process. The excavation of foundations, general earthworks and earth removal tasks are activities which involve the machine operator in a series of repetitive operations. Full or partial automation may improve excavation productivity, efficiency and operator safety, especially in applications such as underground mining or the removal of hazardous waste.

The Engineering Department at Lancaster University has a long record of research into autonomous excavation. In particular, the Lancaster University Computerized Intelligent Excavator (LUCIE) is based on a commercial manual hydraulic excavator (Fig. 1), but with an on-board computer system in place of a driver to control the hydraulics and therefore the machine [1-3].

The objective is to develop an intelligent excavator that can autonomously dig a trench in virgin ground without human intervention. Smooth, fast and accurate control of the excavator joints is an essential component of the system. In this regard, the present paper applies the Proportional-Integral-Plus (PIP) methodology to the joint control problem. Such PIP controllers can be interpreted as a logical extension of conventional PI/PID algorithms, but with inherent model-based predictive control action [4-5].

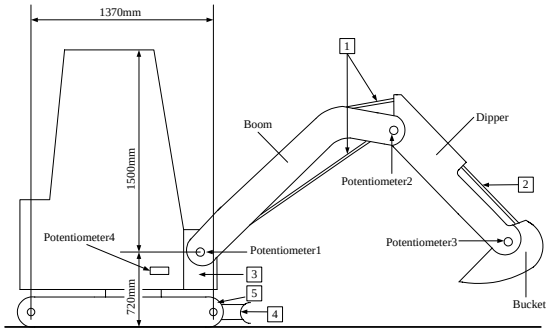


Figure 1. The LUCIE Excavator.

Here, Non-Minimal State Space (NMSS) models are formulated so that full state variable feedback control can be implemented directly from the measured input and output signals of the controlled process, without resorting to the design of a deterministic state reconstructor or a stochastic Kalman filter.

Over the last few years, such NMSS/PIP control systems have been successfully employed in a range of practical examples, including piling rig positioning [6] and LUCIE [3]. However, in the latter case, the nonlinear joint dynamics can sometimes yield an oscillatory response for bucket position. In order to maintain smooth control, therefore, previous control algorithms have typically utilised a relatively slow control action.

By contrast, the research described below develops a straightforward to implement, *gain scheduled* PIP control system, in order to increase the speed of response. Here, the differing joint dynamics when the digger arm is opening or closing, are accounted for by the design of separate PIP control algorithms in each case. The new approach is evaluated in both simulation and field tests.

2. THE EXCAVATOR

The tracked excavator used as the platform for the LUCIE project is a JCB 801 mini excavator, as illustrated in Fig. 1. The machine has an operating weight of 1.4 tons, is less than one meter wide, has a bucket capacity of approximately 940kg and a maximum vertical digging depth of about 1.5m.

It has been refitted with electro-hydraulic servo valves, associated sensors and a computer control system, to allow for the development, experimental evaluation and refinement of the new intelligent control systems.

All of the arm movements are hydraulically driven as follows (referring to the numbers in Fig. 1):

1. Movement of the arm in the (x, y) vertical plane uses two hydraulic cylinders that control the boom and dipper respectively.

2. Rotation of the bucket at the end of the dipper, in the same vertical plane, uses another cylinder.
3. Rotation of the cab at its connection to the undercarriage effectively provides movement for the arm in a horizontal plane (slew).
4. Movement up and down of a dozer blade at the front of the undercarriage.
5. Independent movement of two parallel caterpillar tracks for skid-steer movement of the whole platform.

The sensory equipment built into LUCIE is summarised below:

- Four potentiometers on the joints for angle measurement.
- A two-axis tilt sensor.
- A Leuze RotoScan RS 3 optical laser distance sensor for obstacle detection at a range of up to 15m.
- A Trimble 7400Msi series satellite GPS for location and navigation.

Finally, as illustrated by Fig. 2, LUCIE relies on three embedded PC 104 computers, each responsible for one of the three tasks listed below. The communication between these computers is provided by CAN-Bus (Controller Area Network).

- **High Level Controller (HLC)** is responsible for the planning of activities and navigation, such as which trench to dig first.
- **Low Level Controller (LLC)** is responsible for driving the valves and tracks by commands that are issued either by other processors or the joysticks. It also accepts inputs from the various potentiometers giving positional feedback. This component is the focus of the present paper.
- **Safety Manager (SM)** acts as the excavator conscience ensuring that the machine remains in a safe stable condition.

3. NMSS/ PIP CONTROL

Since there is little interaction between the dipper and boom hydraulics, the present research is based on the simplest multiple loop, single input, single output control algorithms, i.e. PIP controllers are designed for each joint separately.

In order to develop a linear PIP algorithm, a linearised representation of the system is first required. In this regard, the small perturbation behaviour of each joint is approximated by the following discrete-time transfer function,

$$y_k = \frac{b_1 z^{-1} + \cdots + b_m z^{-m}}{1 + a_1 z^{-1} + \cdots + a_n z^{-n}} u_k = \frac{B(z^{-1})}{A(z^{-1})} u_k \qquad (1)$$

where y_k is the joint angle (degrees) and u_k is the applied voltage, expressed as a percentage in the range -1000 to +1000. Positive and negative inputs open or close the joint respectively. Here, $A(z^{-1})$ and $B(z^{-1})$ are appropriately defined polynomials in the backward shift operator $z^{-i} y_k = y_{k-i}$.

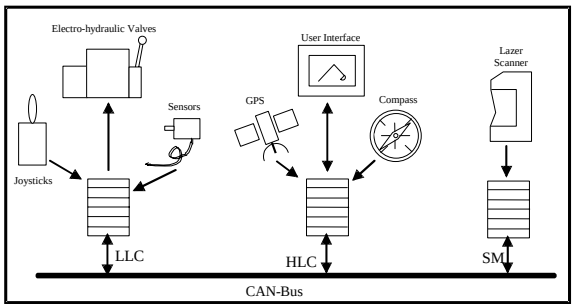


Figure 2. LUCIE Control System Architecture.

For convenience, any pure time delay of $\delta > 1$ samples can be accounted for by setting the $\delta - 1$ leading parameters of the $B(z^{-1})$ polynomial to zero.

The present research utilises the Simplified Refined Instrumental Variable (SRIV) algorithm to estimate the model parameters [7-8]. The model structure first needs to be identified, i.e. the most appropriate values for the triad $[n, m, \delta]$. The two main statistical measures employed to help determine these values are the coefficient of determination R_T^2, based on the response error; and YIC (Young's Information Criterion), which provides a combined measure of model fit and parametric efficiency [7-8].

These statistical tools and associated estimation algorithms have been assembled as the CAPTAIN toolbox within the Matlab® software environment (www.es.lancs.ac.uk/cres/captain). The authors can be contacted for further details about this toolbox

It is easy to show that the model (1) can be represented by the following linear Non-Minimal State Space (NMSS) equations,

$$\begin{aligned} \mathbf{x}_k &= \mathbf{F}\mathbf{x}_{k-1} + \mathbf{g}u_{k-1} + \mathbf{d}y_{d,k} \\ y_k &= \mathbf{h}\mathbf{x}_k \end{aligned} \qquad (2)$$

where, **F**, **g**, **d** and **h** are defined by [3-6]. The $n+m$ dimensional *non-minimal* state vector $\mathbf{x}_k$, consists of the present and past sampled values of the input and output variables, i.e.,

$$\mathbf{x}_k = \begin{bmatrix} y_k & y_{k-1} & \cdots & y_{k-n+1} \\ & u_{k-1} & \cdots & u_{k-m+1} & z_k \end{bmatrix}^T \qquad (3)$$

Here, $z_k = z_{k-1} + \{y_{d,k} - y_k\}$ is the *integral-of-error* between the reference or command input $y_{d,k}$ and the sampled output y_k. Inherent type 1 servo-mechanism performance is introduced by means of the *integral-of-error* state z_k. If the closed-loop system is stable, then this ensures that steady-state tracking of the command is inherent in the design.

The control law associated with the NMSS model (2) takes the usual State Variable Feedback (SVF) form,

$$u_k = -\mathbf{k}\mathbf{x}_k \qquad (4)$$

where $\mathbf{k} = [f_0 \; f_1 \cdots f_{n-1} \; g_1 \cdots g_{m-1} \; -K_I]$ is the SVF control gain vector. In more conventional block-diagram terms, the SVF controller (4) can be implemented as shown in Fig. 3.

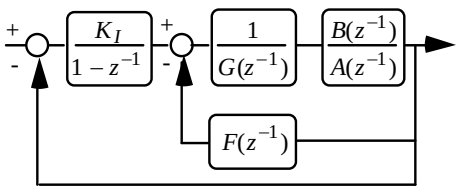


Figure 3. PIP control in feedback form.

It is clear from Fig. 3 that PIP control can be considered as one particular extension of the ubiquitous PI controller, where the PI action is, in general, enhanced by the higher order forward path and feedback compensators $1/G(z^{-1})$ and $F(z^{-1})$,

$$F(z^{-1}) = f_0 + f_1 z^{-1} + \cdots + f_{n-1} z^{-(n-1)}$$
$$G(z^{-1}) = 1 + g_1 z^{-1} + \cdots + g_{m-1} z^{-(m-1)} \quad (5)$$

However, because it exploits fully the power of SVF within the NMSS setting, PIP control is inherently much more flexible and sophisticated, allowing for well-known SVF strategies such as closed loop pole assignment, with decoupling control in the multivariable case; or optimisation in terms of a conventional Linear-Quadratic (LQ) cost function, determined by the steady state solution of the ubiquitous discrete-time matrix Riccati equation.

Note that, in the NMSS/PIP case, the elements of the LQ weighting matrices have particularly simple interpretation, since the diagonal elements directly define weights assigned to the measured input and output variables.

4. GAIN SCHEDULING CONTROL

Gain scheduling is a powerful approach for the control of nonlinear and time-varying systems because of its simplicity and ability to use linear design methods [9]. The design of a gain scheduling controller involves the following steps [10],

1. Linearize the plant about a finite number of representative operating points.
2. Design linear controllers for the plant linearizations at each operating point.
3. Interpolate the parameters of the various linear controllers to achieve adequate performance of the linearized closed loop system at all points where the plant is expected to operate – the resulting family of linear controllers is the gain-scheduled controller.
4. Implement the gain scheduling controller on the nonlinear plant.

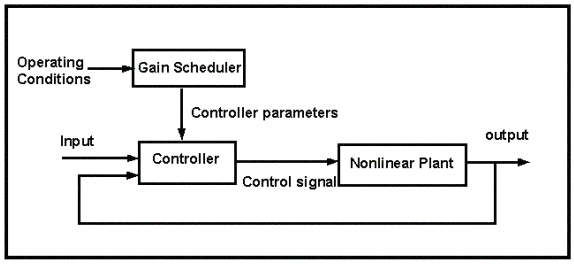


Figure 4. Gain-scheduled control.

The parameters of the gain scheduling controller evolve as functions of the plant states, inputs, outputs and exogenous parameters, or some combination of these. The gain-scheduled controller takes the general form illustrated by Fig. 4.

5. EXCAVATOR CONTROL

During automatic digging, the most important sub-target is to keep the bucket moving along a specified path quickly, smoothly and accurately. The straight line is the most common path employed, as in the case of dragging a flat bottomed trench in the ground, or moving the earth from the digging point to the dumping point. For high efficiency, such activities should be completed as quickly as possible.

Numerous researchers have considered this problem, with various degrees of success. For example, Nguyen [11] applies feedback linearization methods. In this case, experimental results indicate that the performance can be degraded by the presence of noise. Fuzzy moving sliding mode [12] and impedance [13] controllers have similarly been developed for robot excavators.

Budny [14] considers control of an excavator bucket in straight lines by applying Danfoss PVG 32 load-independent hydraulic valves. Here, the bucket was moved along planar vertical and horizontal lines in both free space and in a soil box filled with homogenous mildly humid sand. Although the accuracy is kept within 10cm, the velocity achieved was relatively low, only about 2m/min.

Similar tests for LUCIE, utilising conventional PI methods [1], also require slow movement of the bucket in order to maintain accurate control. This is the motivation for the development of a new PIP algorithm for regulating the joint dynamics [3]. The following section builds on this earlier research, by now developing a scheduled gain PIP control system for LUCIE and implementing further field tests.

6. CONTROL DESIGN FOR LUCIE

In order to identify the dominant dynamics of the excavator, joint data are collected for typical step changes in the applied voltage. In this case, the SRIV algorithm, combined with the YIC and R_T^2 identification criteria, suggest that a first order tranfer function model with either 1 or 2 samples time delay provides the best explanation of data across a wide range of operating conditions [3].

Furthermore, in common with many other hydraulic systems, such as [6], it is clear that both the boom and dipper angles behave as integrators, with an almost constant rate of change for a given input signal. For simplicity in the initial study, therefore, the following model structure is employed,

$$y(k) = \frac{b z^{-1}}{1 - z^{-1}} u(k) \quad (6)$$

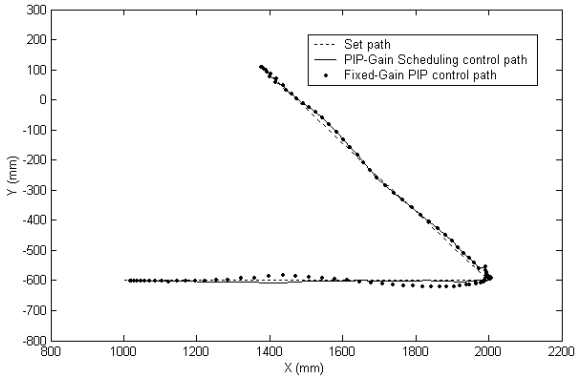


Figure 5. Simulation of bucket movement comparing fixed-gain PIP (dots), PIP-gain scheduling (solid) and the set path (dashed).

Here, $y(k)$ represents the boom or dipper joint angle, $u(k)$ is the associated input voltage and the numerator b is estimated using SRIV methods. A sampling rate of 0.1 seconds is utilised throughout, since this is within the capabilities of the on-line computer and is found to work well in practice.

Note that for all the analysis in the present paper, the dead-zone is removed at the data collection stage, so that a positive voltage scaled from 0 to 1000 causes the boom to open, whilst a negative voltage up to –1000 reverses the direction. In this manner, the boom can be positioned at an angle between 0 and 60 degrees, where the later figure represents fully open. Similarly, a scaled input voltage to the dipper in the range -1000 to 1000 causes the dipper angle to vary from -30 (fully open) to -140 degrees.

For example, a boom opening experiment with an input voltage of 60 yields the model (6) with $b = 0.005$. In this case, specifying closed loop poles at 0.6 on the real axis of the complex z-plane, yields robust PIP control of the boom angle when the latter follows an opening trajectory. Here, the PIP control gain vector is defined as follows,

$$\mathbf{K} = [128 \;\; -32] \tag{7}$$

By contrast, the PIP control algorithm for a decreasing boom angle, is based on a boom closing experiment with an input voltage of -40, which yields $b = 0.018$ and,

$$\mathbf{K} = [35.6 \;\; -8.9] \tag{8}$$

A similar approach is taken for the dipper angle. With an input voltage of –100 and 100 to open or close the joint, $b = -0.012$ and $b = -0.018$ respectively. The associated PIP gain vectors are given by,

$$\mathbf{K} = [-53.3 \;\; 13.3] \tag{9}$$

and

$$\mathbf{K} = [-35.6 \;\; 8.9] \tag{10}$$

The above feedback gains (7) to (10) are utlised in the design of a scheduled control algorithm. Here, the key decision is how to choose appropriate control gains for each sampling period. In this regard, the controller utilizes a comparison between the current measured joint angle and the expected (commanded) angle of the arm at each sampling instant. For example, if the angle is larger than its expected value, the scheduler will choose the control parameters for the joint closing case.

For this particular implementation, interpolation between different operating points (for example using fuzzy methods) does not appear necessary. The inherent robustness of the basic PIP design over a range of operating levels ensures that the simple approach discussed here works very well, while the final design is particularly straightforward to implement in practice, as discussed below.

7. SIMULATION EXPERIMENTS

To demonstrate the behavior of the proposed control scheme, consider the simulation response shown in the polar coordinate plot of Fig. 5. Here, the simulation is based on a combination of excavator kinematics and data-based nonlinear dynamic models, implemented using the MATLAB/ SIMULINK© package, as described by reference [3].

The objective of this simulation experiment is to move the bucket from its initial position (1378, 109) to (2000, -600), and then to (1000, -600), where the (x, y) coordinates are given in mm from the point of attachment of the boom to the vehicle.

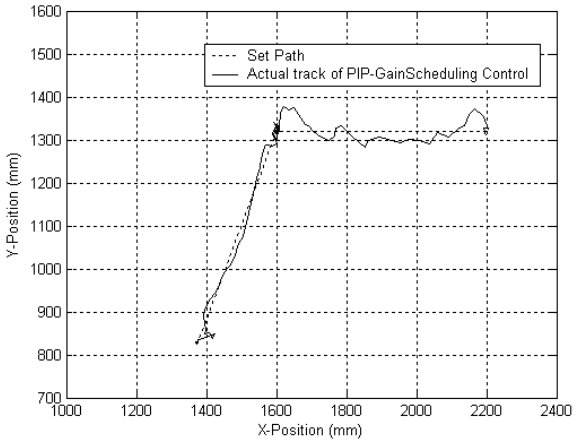
To avoid discontinuous force variations that may cause the arms to jerk during operation, the acceleration of the arms should be continuous. In this regard, the trajectory between each set of coordinates takes the form of a 5th order polynomial ‘jerk-free’ straight line as suggested by [15]. The objective is to complete the whole motion within 5 seconds, including a wait of 0.3 seconds at the initial position.

In Fig. 5, the bucket is moved along the defined straight-line trajectories well within the demanded time limitation. Compared with the fixed-gain PIP controller based on equations (8) and (10) only, the gain-scheduling algorithm provides more accurate and smoother performance. Although the latter difference is relatively small, these results presage the likely improvement of the approach when applied to the actual system, where any errors are multiplied.

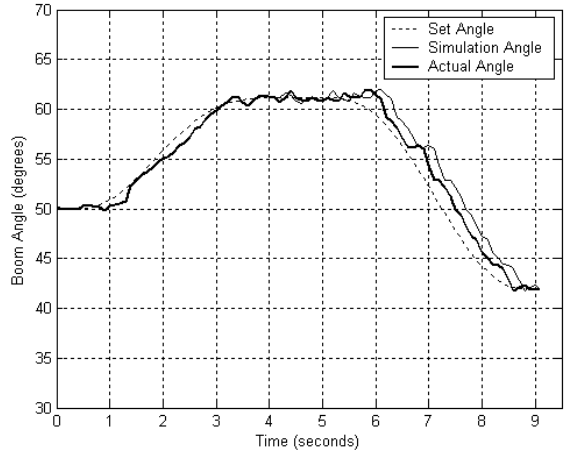
Although not shown in Fig. 5, both PIP algorithms provide considerably improved performance over a PID controller obtained using the Ziegler-Nichols ultimate sensitivity method. As discussed by [3], the latter algorithm only provides accurate control for relatively slow movements of the bucket.

8. FIELD EXPERIMENTS

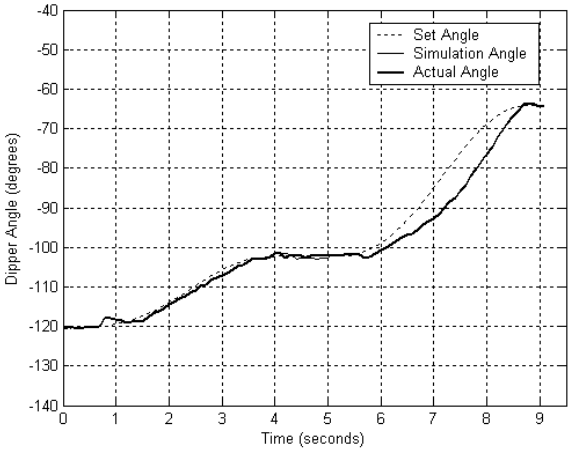
The test illustrated here is designed to move the bucket along a desired oblique straight line and a horizontal straight line. For safety reasons, all the bucket movements for these preliminary field tests are in air only.



(a) Bucket position.



(b) Boom angle.



(c) Dipper angle.

Figure 6. Implementation results, comparing the desired trajectory, the simulation response and LUCIE experimental data.

A Turbo C++ programme was written by the 1st author and executed under the DOS 6.0 operating system, to realize the PIP-gain scheduling control algorithm. During the experiment, the hydraulic pressure is kept at 1.1×10^7 Pa.

Fig. 6 (a) shows the bucket moving from its initial position at (1368, 829) to (1600, 1320) along an oblique straight line in 4 seconds. Following a programmed 1 second delay, the bucket moves to (2200, 1320) along a horizontal straight line in a further 4 seconds. As before, the (x, y) coordinates are given in mm from the reference point.

As expected, the bucket moves closely along the reference path with an error magnitude less than 20mm during the oblique straight line motion. When the bucket moves along the horizontal straight line, the error magnitude is maintained lower than 50mm.

Since the bucket position is decided by the angle of boom and dipper according to the kinematic relationship of joints established by [2], the key to the proposed bucket position control depends on the respective boom and dipper angle controllers. In this regard, Fig. 6 (b) and (c) show the tracking responses of the boom and dipper respectively. In these figures, the actual angles of the boom and dipper closely follow the equivalent simulated values, attesting to the accuracy of the previously developed nonlinear simulation model [3], as well as the associated linear transfer functions utilised for control system design.

However, it is clear from Fig. 7 (b) that there is some vibration when the boom tracks the desired angle. Although this vibration is less than 1.5 degrees, it yields a noticeable positional error in bucket position because of the long transmission length of over 1.5m. This is the main factor that leads to bucket position errors. Most commonly, such vibration occurs when: (i) the boom changes its direction of motion, e.g. from opening to closing; (ii) any movement from stationary; or (iii) big changes of drive-demand even if they are in the same direction.

Another factor that can partially explain the position errors are delayed responses from the hydraulic system, i.e. the response time of the hydraulic system sometimes lags behind the real time requirements. In particular, longer pure time delays than the unity implied by equation (6) sometimes occur. For this reason, the authors are presently considering PIP controllers based on models with longer time delays. In fact, one of the key advantages of PIP control over conventional PI/PID design, is that the former approach robustly accommodates such long pure time delays [3-4].

9. CONCLUSIONS

In moving towards autonomous excavation for a heavy hydraulic excavator, fast and smooth bucket position control is an essential step. However, this requirement presents a difficult control problem because of the nonlinear excavator dynamics.

The present paper follows up earlier research into Proportional-Integral-Plus (PIP) control of the Lancaster University Computerized Intelligent Excavator or LUCIE [3], by now developing a gain scheduled system. Here, appropriate PIP control gains are chosen at each sampling instant, based on the current operating state of the excavator arm.

Unmodelled dynamic effects such as vibrations of the boom, together with occasional large time delays, both influence the tracking performance of the bucket

position controller. Nonetheless the results obtained in both simulation and preliminary field tests are very promising. They show that the PIP-gain scheduling control system is able to drive the bucket along desired trajectories, with an accuracy and speed considerably higher than previously obtained.

In particular, the accuracy is within 50mm, while the velocity reaches 9 meters per minute. These are within the requirements of normal excavation tasks. In fact, the new control system offers performance that is comparable to that achieved by an average human operator.

The scheduler utlised to date is very straightforward: the parameters are divided into two groups based on whether the arm is opening or closing. However, the authors are presently considering more sophisticated approaches to the scheduling. For example, one solution is to divide the parameters into groups based on the different velocity requirements.

Another novel research area currently being investigated at Lancaster, in order to improve PIP control in the case of nonlinear systems, is based on the State Dependent Parameter (SDP) system identification methodology. Here, the nonlinear system is modelled using a quasi-linear model structure in which the parameters vary as functions of the state variables [16]. Preliminary simulation studies have demonstrated the utility of such models in the design of SDP-PIP control systems [17].

Acknowledgments

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PROSPECTS FOR AUTOMATION AND ROBOTICS REVOLUTIONIZING ORDINARY CONSTRUCTION SYSTEMS THROUGH ADVANCED INFORMATION TECHNOLOGY

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ABSTRACT

The wave of advanced information technology will drastically change the ordinary construction systems in the Japanese construction industry. The procurement and delivery systems of the Ministry of Land, Infrastructure and Transportation will also be computerized. Construction robots need to be regarded as a construction system in the context of the sophistication of information systems rather than simply as a machine with mechanical motions and automated functions.

This paper describes the current situations of Automation and Robotics in each field of earth work, foundation work, tunneling work, and offshore work, and provides their outlooks and challenges in the future.

Key words:
future vision of earthwork, unattended construction work , advanced information systems, Tunnel Boring Machine, future prospect for construction robots

1. INTRODUCTION

Japan's construction industry has begun to experience labor accidents, shortages of skilled workers, and other problems. Moreover, demand for cost cutting is intensifying, leading to higher expectations for new construction technologies and efficiencies. These trends will likely continue. To address these issues, the construction industry is closely examining the use of information technologies and robotics for construction.

This paper describes the current situation regarding construction robots in Japan and presents an idealized scenario for construction work based on a study of current challenges and future prospects.

2. INFORMATION TECHNOLOGY AND CONSTRUCTION ROBOTS

Rapid progress in information technology is beginning to have a dramatic effect on the daily construction management practices of contractors. This trend is being accelerated by the efforts of the Ministry of Land, Infrastructure and Transport to establish procurement and electronic delivery systems based on the 'Construction CALS/EC' concept and compliance with ISO standards.

Figure 1 shows the flow of information during a construction project. E-construction is a system by which a contractor can access information common to each trade and incorporate it into the construction work. Adding mechatronics (a controlling function) to this system creates robotics construction. In other words, advanced information technology, system sophistication, and mechatronics are keywords for construction robots.

The following sections shed light on Japan's current state of automation and the use of robotics for construction as well as describe future challenges and outlooks.

3. CURRENT STATE OF ROBOTICS CONSTRUCTION IN EACH TRADE

3.1 Automation and robotics in earthworks

The use of robotics in Japan for large-scale earthworks made a great leap forward in 1993 when unattended operations were carried out at Mt. Unzen Fugendake. Between 200-300 million m^3 of volcanic debris from an eruption was removed using remotely controlled breakers, backhoes, bulldozers, and dump trucks. This large-scale application of robotics was followed by the remotely controlled construction of an 870 m-long long debris barrier using the RCC (Roller Compacted Concrete) method, as shown in Photo 1 and Figure 2.

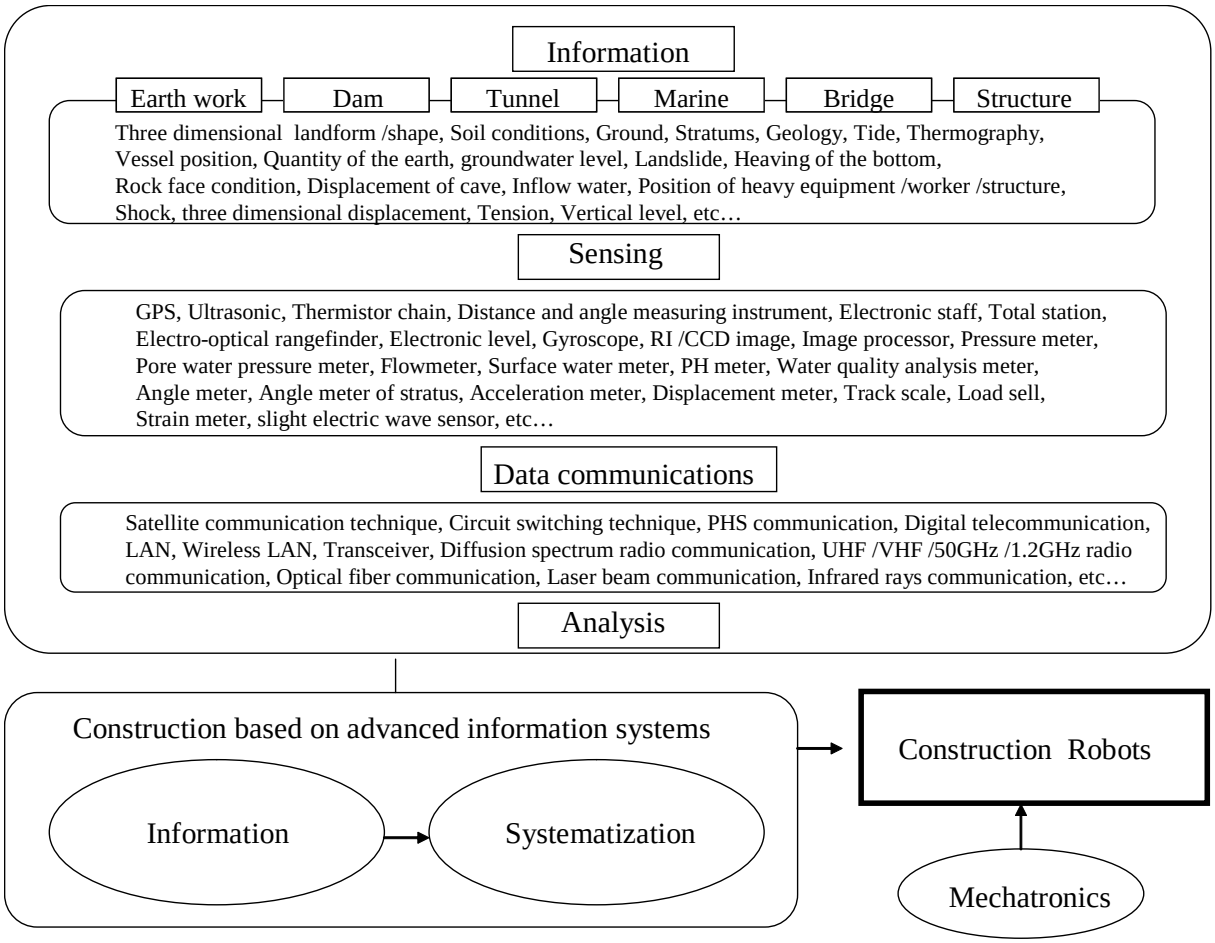
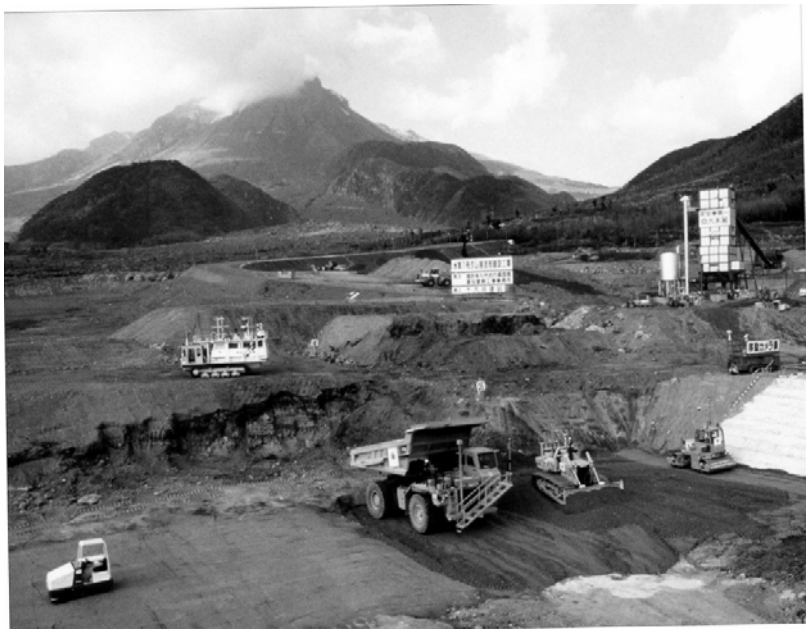


Figure 1 The flow of information during construction project

This was the first application of the GPS compaction control system to this type of work. It is now widely used in other earthworks projects. Information technologies that were developed during the work are now used by the construction industry to work out optimal heavy machinery plans and earth conveyance plans, substantially reducing construction time and costs.

Figure 3 shows a system for using laser control to automate measurements of a three-dimensional topography in an area specified on an image. This unattended measuring robot operates at night in order to avoid the numerous numbers of construction machinery that come and go on a site during the day.



Phote 1 Remotely controlled construction of RCC Dam

The system can also perform kymographic observations, recording geographically distinctive points on the face of a cliff through image processing and automatically tracking the recorded points. The system is attracting attention for its potential use in disaster prevention systems as well as for its applications in earthworks projects. It is also considered a basic technology for robotics construction in the future.

3.2 Automation and robotics for foundation work

Foundation work has greatly benefited from robotics, which can carry out diaphragm wall work, caisson work, and other tasks, relieving human workers of hard and dangerous work and improving work efficiency and accuracy.

Using robotics, a large diaphragm wall was constructed as an earth retaining and water cut-off wall for an underground LNG tank. Robotics was also used to build a 119 m-deep, 2.8 m-thick wall for the “Kawasaki Man-made Island” on the Trans-Tokyo Bay Highway. As these cases show, as diaphragm walls grow larger, greater efforts are made to automate measurement management and other tasks in order to improve construction accuracy and work efficiency.

On the other hand, with the pneumatic caisson method, structures are submerged as they are constructed. Workers in these structures have long suffered from poor working environments and exposure to high atmospheric pressures. Figure 4 shows a chamber and a series of unattended operations, including excavation, loading, and earth discharge, that are remotely controlled from a room above ground. The system was recently made more sophisticated by the incorporation of a function that

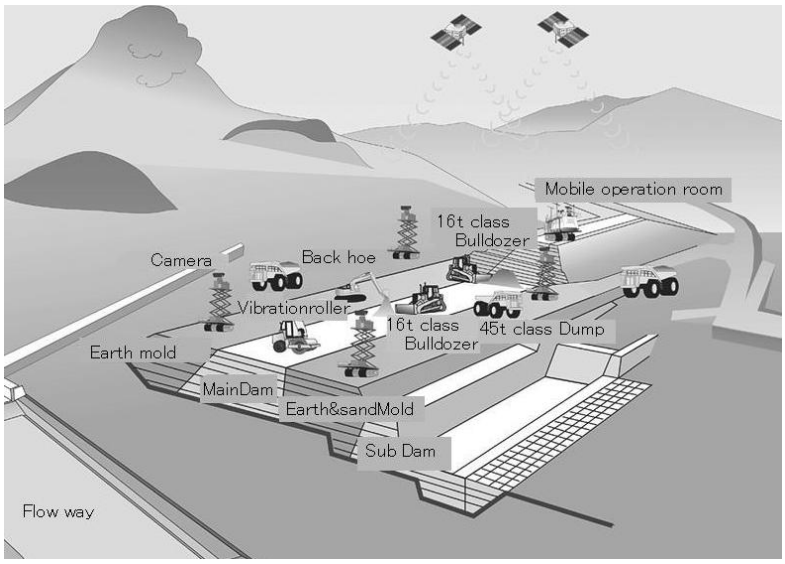


Figure 2 Unattended remotely controlled construction system

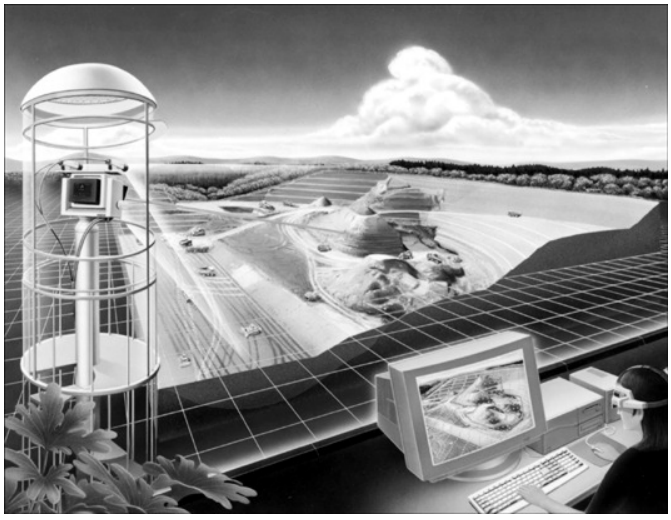


Figure 3 Survey robot using laser and image control

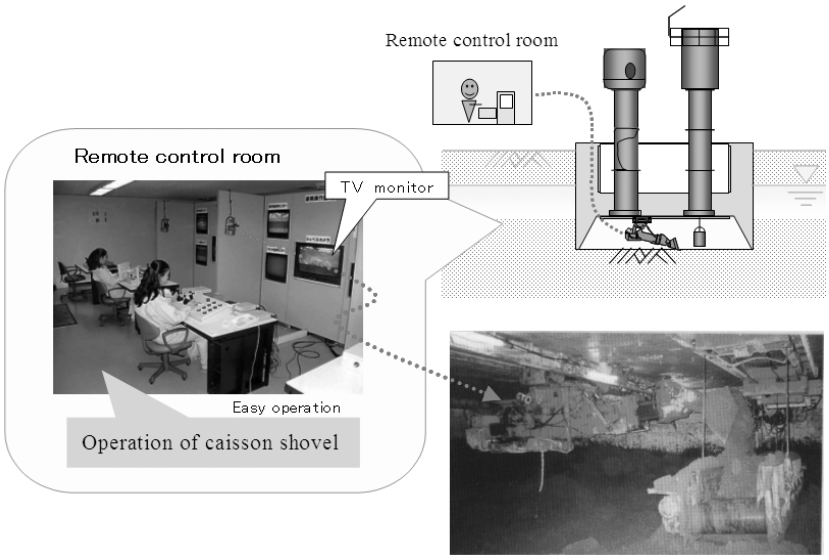


Figure 4 Remotely controlled pneumatic caisson system

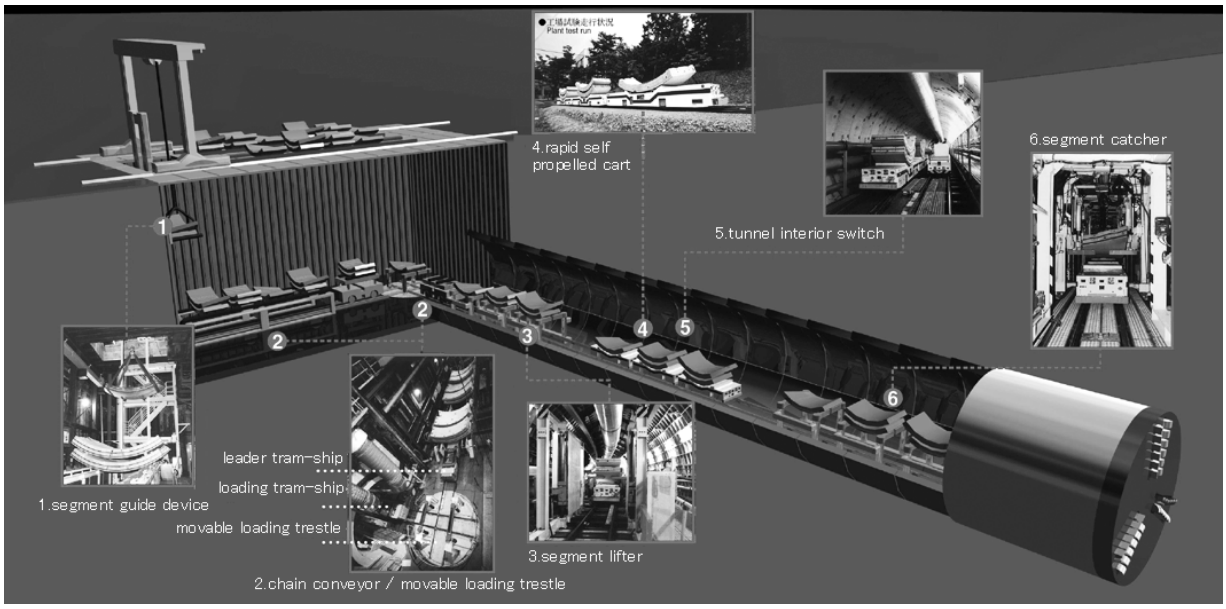


Photo 2 Segment conveyance Robot

automatically measures the track of a boring machine and the shape of the excavation ground.

3.3 Automation and robotics in tunneling work

Shield tunneling is drawing great attention as a way to reconstruct urban infrastructure without causing congestion.

The shield tunneling excavation process has been fully automated, with robotics controlling the launching speed of the machine, the rotation speed of the cutter, the location, position, and orientation of the machine, the water pressure at the tunnel face, pumping operations, etc. The segment assembly process has also been fully automated, with robotics being used for in-tunnel conveyance, assembly, and other tasks. Photo 2 shows a segment conveyance robot. Managed from a central control room, this fully automated system controls a variety of tasks, from the arrival and storage of segments, to their retrieval and conveyance to a tunnel face by means of automated guided vehicles.

Photo 4 Hard-rock free-section excavator robot

Photo 3 Tunnel Boring Machine

A number of problems have surfaced regarding the New Austrian Tunneling Method (NATM), which is widely used to construct mountain tunnels. These problems include difficulties in automating blasting, a poor tunnel environment due to dust, and labor accidents. This situation has accelerated the introduction of robots, including TBMs (Tunnel Boring Machines) and free-section excavators.

Modern TBMs offer safe and rapid excavation in the complex or soft ground conditions characteristic of Japan. TBMs are being used in a rapidly increasing number of tunnel projects. Photo 3shows the world's

largest TBM. With a diameter of 12.84 m, it has been used to excavate two-lane road tunnels and other large tunnels. It is an example of the remarkable technological progress being made in the development of TBMs, particularly in the application of IT to such sophisticated tasks as probing the ground ahead. This has helped to achieve high-performance robotics construction.

In contrast, hard-rock free-section excavators are environmental-friendly, hard-rock boring machines that eliminate the need for blasting. These excavators are gaining attention not only for their environmental friendliness but also as a blast-free method that has little effect on adjoining structures, does not harm the ground, and can excavate watertight spaces having any desired cross-section. As Photo 4 shows, this type of excavator is designed to use reaction forces. It has four grippers and supports the ground at two points. The disc cutter moves vertically and horizontally, creating pressure that breaks the rocks. Automated operation reduces energy needs, increases excavation efficiency, and improves the quality of the construction work.

3.4 Automation and robotics in offshore work

By moving offshore, Japan has found a means of expanding the urban infrastructure of its congested cities. Current projects include extending Haneda Airport out to sea and constructing artificial islands near the Kansai and Chubu Airports. As these cases indicate, offshore work is being carried out in soft ground and at increasingly greater depths, which creates difficult working conditions. A shortage of qualified divers is also a serious problem. As a result, the industry is optimistic about the use of robotics in offshore work.

Photo 5 shows a walking dredging robot. Through onshore control, it walks on eight legs along the sea bottom, performing automatic dredging operations in a safe and efficient manner.

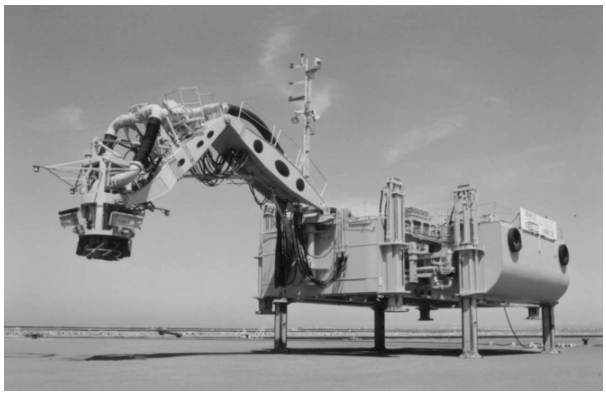


Photo 5 Walking dredging robot

4. CHALLENGES AND PROSPECTS FOR ROBOTICS CONSTRUCTION

4.1 Current state and challenges of robotics construction

The Japan Society of Civil Engineers Committee on Automation and Robotics in Construction conducted a survey on the current use and technical level of robotics in each work task. The results were categorized into levels from A to C. In Level A, the robots operate automatically according to the decisions is makes on its own. In Level B, the robots operate according to decisions made by human operators. Level C means basic mechanization of construction work.

The study revealed that Level A is the most commonly seen level in shielding work. Many work tasks are using robots on a trial basis, however, and a range of problems must be solved before they can be used more widely.

Level C is also quite visible in shielding work, indicating that many operations require human involvement and judgments even in shielding work, which seems to be ahead of the other trades in the introduction of automation and robotics. The committee noted that robots working alongside humans must also be considered for certain cases.

The committee found that Levels B and C predominated in gravity dam and offshore construction. Few projects were at Level A. The report pointed out that B- and C-level projects incorporate many types of activities and these are different in nature from shielding and other types of construction work, which are characterized by continuous streams of work. To promote automation and robotics in various fields, the study suggests using IT to automate operations in each trade as well as creating more sophisticated systems as a whole.

4.2 Future prospects for robotics in construction

In the future, advanced information technology will become more tightly integrated with construction machinery, creating highly sophisticated robotic construction systems that can provide greater efficiency, productivity, and safety.

Figure 5 depicts mountain tunnel construction in the future using an advanced, smart TBM. The machine operates according to a tunneling plan developed from a variety of information sources. The plan is constantly updated during the course of excavation with data from the machine’s current position.

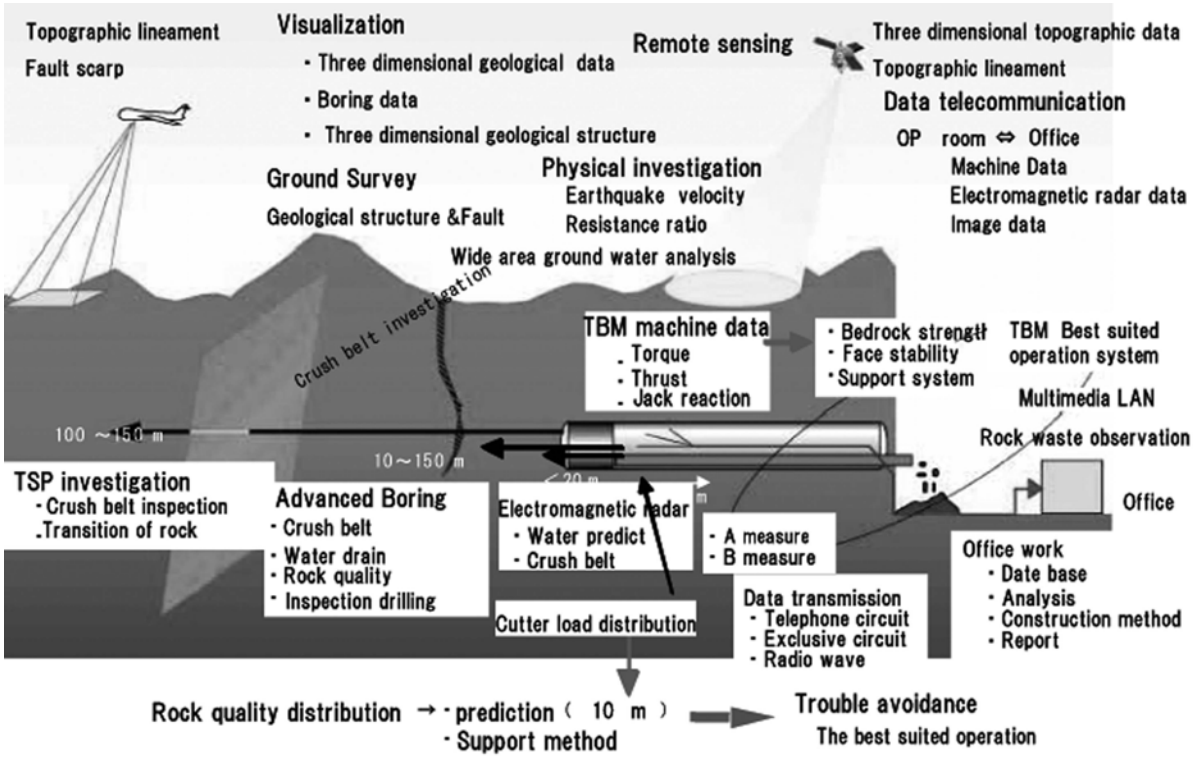


Figure 5 Future prospect of smart TBM in tunnel construction

As seen above, construction robots in the 21st century will likely be equipped with advanced information technologies and designed as sophisticated systems that operate alongside human workers.

ACKNOWLEDGEMENTS

Since its foundation in 1985, the Committee on Automation and Robotics in Construction of the Japan Society of Civil Engineers has been active in a variety of fields relating to automation and robotics in the construction industry. This paper presents some of the results of those activities. I would like to express my sincere thanks to the colleagues with whom I have worked.

I also would like to gratefully acknowledge The Tokyo Electric Power Co., Inc., Taisei Corporation, and Penta-Ocean Construction Co, Ltd., for furnishing me with photos, materials, and information.

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A BUCKET DISCHARGE CONTROL FOR A BACKHOE EXCAVATOR

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Abstract
The study presents a practical, optimal control system of the discharge process of a backhoe bucket. The process begins when the bucket is filled and ends when the bucket come back to the digging position. In the process, several geometrical constraints are considered, such as, clearance dimension, and obstacles in the excavator working zone. In other words, the operator has to give the path of the discharge process. The problem is considered as a multi body, chain system, driven by hydraulic actuators. The system is decomposed in free body diagrams of separate elements. Starting from the bucket, each element is solved separately, as many times, as many it is needed to get optimal time for given actuator forces.

Key Word: excavator, multi body systems, optimal control, hydraulic actuators, recursive multi body dynamics.

1. INTRODUCTION

A relatively large part of the excavator work time is taken by hauling, dumping and return of the bucket to its digging position. This part of the excavation process is having at least two features, which distinguish them from the earth moving work. The first one, is that the bucket discharging should be considered as a dynamic process. The soil digging, in the contrary, can be regarded as a quasi-static process, in which the acceleration of the excavator attachment members could be neglected.
It is then the aim of the study to present a practical control system of the discharge process of a backhoe bucket. The process begins when the bucket is filled and ends when the bucket came back to the digging position. In the discharge control process several geometrical constrains are taken into consideration. First of all, clearance dimension have to be defined. Secondly, all possible obstacles in the excavator working zone should be considered. In the others words, the operator has to define the trajectory of the bucket motion, assuming its time duration.
The discussed problem consists in optimization of a multi body system dynamics (MSD) with constraints and actuators specific for hydraulic driven machines. It kinematics and dynamics are close to the mechanics of robots. The differences are in environmental and working conditions, hydraulic actuators and randomness of working conditions.
Since last two decades, a large number of publications and monographs are devoted to kinematics and dynamics of systems of rigid bodies and their applications to robotics. Monograph by Duffy [5] and Wttenberg [12] together with edited by Schiehlen handbook[9], are very good sources of the knowledge on MSD. One of the very important branch of MSD is robots dynamics (RD). Also in this field, the number of works is very large, as the problem is of scientific and of important applications.
Only in recent years RD started to be investigated in the field of earth moving machines, mostly in excavators (Budny et al [4], Skibniewski [10].
A profound knowledge in MSD get the possibilities of investigating optimal control of considered systems. A pioneer work on optimal control of manipulators, dealing with analytical and numerical approach to the problem, is due Akulenko et al [1]. A general survey of numerical methods for trajectory optimization, showing a wide range of possible applications, is presented by Betts[3]. Due the complexity of optimal control problems, recently, some attention is paid to detailed, problem oriented methods (Furukawa [7], Hu et al [8] and Eberhardet al [6]. Also the present study is an oriented method which can be applied to bracket kinematic chains.
The paper starts with motion description of the excavator boom, arm and bucket motion. The Lagrange's equations are derived, for this complex system, with four degrees of freedom. It is assumed that the separate hydraulic actuator, with limited power, drives each of the degrees of freedom.
The obtained equations are solved in a recursive way. First, the dynamic of the bucket is considered. Then, the actuator force between the bucket and the arm is applied to the latter. This way, step by step, the dynamics of the boom and excavator body are solved. If some of the actuator forces exceed their limited values, we come back to the bucket increasing the assumed time of discharging. This

causes decreases accelerations and then dynamic forces.
The paper presents a pre-shape input to the discussed control system. It is illustrated with the simplest, possible problem of lifting the excavator bucket in horizontal position.

2. KINEMATICS

Consider an excavator attachment, composed of boom, arm and bucket. Their lengths and angels of rotations are respectively $l_1, a_1, l_2, a_2, l_3, a_3$.
The planar attachment can rotate, together with the excavator booth, by an angle j? (Fig. 1). The operator of the machine is assuming path $\boldsymbol{x_p}$ of the bucket tip in 3D space, together with a_3, the angle of the bucket. The system is driven by hydraulic actuators. It is the aim of the study to design a control system, allowing to travel of the end effector, from initial point $\boldsymbol{x_{po}}$ to a final one $\boldsymbol{x_{pf}}$ in the shortest time.

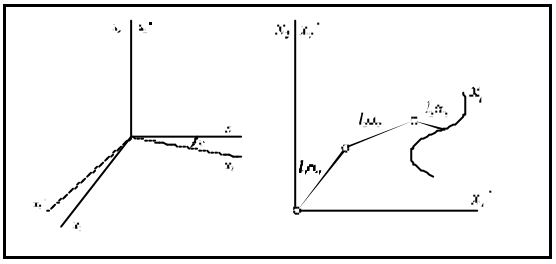

Fig. 1. Coordinate system of excavator's attachment

Denoting by $\boldsymbol{x_p}$ position of the effecter tip, the kinematics of considered mechanism is represented by the vector relation:

$$\boldsymbol{x}_p = \boldsymbol{A}\boldsymbol{l}; \quad \boldsymbol{A} = \begin{bmatrix} c_1c_4 & c_2c_4 & c_3c_4 \\ s_1 & s_2 & s_3 \\ c_1s_4 & c_1s_4 & c_1s_4 \end{bmatrix}; \tag{1}$$

$$\boldsymbol{l}^T = [l_1 \quad l_2 \quad l_3]$$

where c_j and s_j denote $cos\,a_j$ and $sin\,a_j$ respectively. In further considerations the sub index p is omitted as the position of the only of points of the assumed path are considered.
Velocity of the point $\boldsymbol{P}$ $\mathbf{v} = [v_1, v_2, v_3]^T = [\dot{x}_1, \dot{x}_2, \dot{x}_3]^T$ is obtained by taking time derivative of (1):

$$\dot{\boldsymbol{x}} = \dot{\boldsymbol{A}} \cdot \boldsymbol{l} \tag{2}$$

where:

$$\dot{\boldsymbol{A}} = \dot{\boldsymbol{A}}_1 \cdot \dot{a} + \dot{\boldsymbol{A}}_2 \cdot \dot{j};$$

$$\dot{\boldsymbol{A}}_1 = \begin{bmatrix} -s_1c_4l_1 & -s_2c_4l_2 & -s_3c_4l_3 \\ c_1l_1 & c_2l_2 & c_3l_3 \\ -s_1s_4l_1 & -s_2s_4l_2 & -s_3s_4l_3 \end{bmatrix}; \tag{3}$$

$$\dot{\boldsymbol{A}}_2 = \begin{bmatrix} -c_1s_4l_1 & -c_2s_4l_2 & -c_3s_4l_3 \\ 0 & 0 & 0 \\ c_1c_4l_1 & c_2c_4l_2 & c_3c_4l_3 \end{bmatrix}$$

Taking inverse of the $\dot{\boldsymbol{A}}$ matrix, we find the relation of angular velocities $\dot{a}_1, \dot{a}_2, \dot{j}$ of mechanism elements with the tip displacement vector. These angular velocities, in turn, are dependant on the elongation velocities of hydraulic cylinders. This dependence has to be determined from geometrical relations between, cylinders lengths, constant parameters of attachment and a_j. Detailed derivations of these relations are given in [4].
In further considerations, the problem is discretized. The path between $\boldsymbol{x}_0$ and $\boldsymbol{x}_f$ is divided in k_0 elements. Unknowns are the time intervals T_k needed for the bucket tip to travel along k-*th* element of the path.

3. DYNAMICS

Consider a free body diagram of the third element (the bucket) of the system (Fig.2). Gravity forces of the bucket and soil are known. Unknown are reaction forces at the point O_3', being the hinge, between second and third elements. Unknown is also the control moment $\boldsymbol{M}_{C3}$ of the third hydraulic actuator. It is limited ($-\boldsymbol{M}_{C30} \le \boldsymbol{M}_{C3} \le \boldsymbol{M}_{C30}$) by the pressure in the actuator cylinder. Taking moment equation with respect to the hinge O_3' , we come to a vector equation with only one unknown vector and unknown velocities and accelerations $\dot{a}_3, \ddot{a}_3, \dot{j}, \ddot{j}$. The unknowns are found from the solution of optimum control discussed in the next chapter.

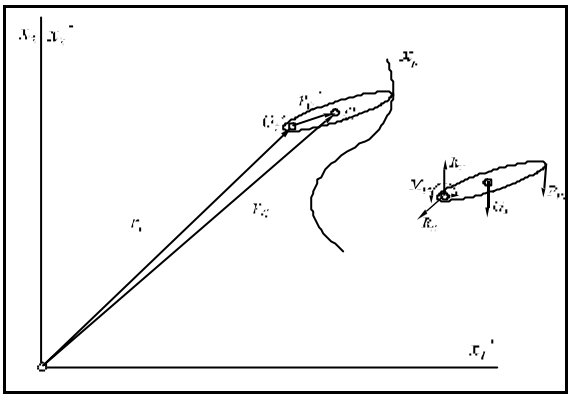

Fig. 2. Free body diagram.

The discussed moment equation can be found from known dynamic relation

$$\frac{d\boldsymbol{J}}{dt} = \dot{\boldsymbol{J}} = \underbrace{\boldsymbol{M}_{3ext}}_{known} + \underbrace{\boldsymbol{M}_{3C}}_{unknown} \qquad (4)$$

where $\boldsymbol{J}$ is the angular momentum of the considered body with respect to O_3', given by the following dynamic relation:

$$\boldsymbol{J}_{O_3'} = \left(\boldsymbol{r}_{3C} \times M_3 \dot{\boldsymbol{r}}_{\boldsymbol{30}}\right) + \dot{\boldsymbol{r}}_{\boldsymbol{30}} \times M_3 \left(w_3 \times r_{3C}'\right) + I_{O_3'} w_3 \qquad (5)$$

where (Fig. 2):

$\boldsymbol{r}_{30} = \boldsymbol{x} - \boldsymbol{l}_3$ - vector between the center of mass *C* and O_3'

M_3 is the mass of the bucket,

w - vector of the angular velocity equal to $\dot{\boldsymbol{a}}_3 + \dot{j}$, and

$I_{O_3'}$ - moment of inertia of the body with respect to O_3' .

After discretization of (4) we get:

$$\boldsymbol{J}_{k+1} - \boldsymbol{J}_k - T_k \boldsymbol{M}_{3ext} - T_k \boldsymbol{M}_{3C} = 0 \qquad (6)$$

with constraints imposed on control torque $-\boldsymbol{M}_{C30} \le \boldsymbol{M}_{C3} \le \boldsymbol{M}_{C30}$.

4. OPTIMUM CONTROL PROBLEM (MINIMUM TIME OF TRAVELING FROM $\boldsymbol{x_0}$ TO $\boldsymbol{x_f}$.)

Consider a minimum time problem by assuming cost function as a sum of all T_k . There are two kinds of constraints – equality and inequality constraints. The first one are moment equations. The latter one, limitations imposed on control moment given with (6). With the following assumptions and notation, our optimum control problem, for the third body, can be stated as follows.

Find:

$$\sum_{k=1}^{k_0} T_k \to min \qquad (7)$$

under constraints expressed by (6).

The Lagrangian of the optimum problem is given by:

$$L = -\sum_{k=1}^{k_0} \left[T_k + \boldsymbol{?}_{1k}\left(\boldsymbol{J}_{k+1} - \boldsymbol{J}_k - \boldsymbol{T}_k \boldsymbol{M}_{3ext} - \boldsymbol{T}_k \boldsymbol{M}_{3Ck}\right) + \right.$$
$$\left. + \boldsymbol{?}_{2k}\left(\boldsymbol{M}_{3Ck} - \boldsymbol{M}_{3Ck}^0\right) + \boldsymbol{?}_{3k}\left(\boldsymbol{M}_{3Ck} + \boldsymbol{M}_{3Ck}^0\right)\right] \qquad (8)$$

Optimality conditions, in the form of derivatives of *L* with respect to design variables T_k and M_{3Ck} for $k = 1,2,\ldots, k_0$ and $i = 1,2,3$ are:

$$\begin{aligned} &\frac{dL}{dT_k} = -1 - \boldsymbol{?}_{1k}\left(\boldsymbol{M}_{3ext} + \boldsymbol{M}_{3Ck}\right) = 0 \\ &\frac{dL}{dM_{3iCk}} = -l_{1k} T_k + l_{2ik} + l_{3ik} = 0 \\ &l_{2k}\left(M_{3ext} - M_{3Ck}^0\right) = 0 \\ &l_{3k}\left(M_{3ext} + M_{3Ck}^0\right) = 0 \end{aligned} \qquad (9)$$

Inspecting (9), we come to the conclusion, that control moment should have one of its extreme values: M_{3Ck}^0 or $-M_{3Ck}^0$. Bearing in mind Pontriagin's general results, we assume one control switching, changing $-M_{3Ck}^0$ to M_{3Ck}^0. It means that we have two sets of equations (4) and (6) with positive and negative value of M_{3Ck}^0

It means, they have to be solved with different initial-boundary conditions. They are:

$$\begin{aligned} &t = t_0; \quad a_3 = a_{30}; \quad \dot{a}_3 = 0; \\ &j = j_{30}; \quad \dot{j}_{30} = 0; \quad \boldsymbol{x} = \boldsymbol{x}_0; \\ &t = t_f; \quad a_3 = a_{3f}; \quad \dot{a}_3 = 0; \\ &j = j_{3f}; \quad \dot{j}_{3f} = 0; \quad \boldsymbol{x} = \boldsymbol{x}_f; \end{aligned} \qquad (10)$$

Once the time t_f of control system is known, we can solve all dynamic equations of the body, finding hinge reactions. Now, we can proceed to the dynamics of the second element (arm). The considerations are exactly the same as with the bucket. We find angular momentum and then moment equations with respect to O_2', hinge

joining first (boom) and second (arm) elements. From these equations, we find control moment M_{2Ck}, needed to move the second element, within the time found solving control problem of the first element. Next, we proceed, in the same way, to the first element finding M_{1Ck}. Finally, we write the moment equation for the booth, again finding its control moment M_{bCk}. From all four elements we are getting control moments. If moments for the booth, the first and second elements are smaller than assumed limit values, then the problem is solved. If one the mentioned moments is larger than its limit value, we have to go back to the first element, decreasing its M^0_{3Ck}, verifying again, through dynamic equations, if the remaining moments are within assumed limit values.

5. EXAMPLE

In order to illustrate the method, in a relatively simple way, we discuss below a planar motion of an excavator bucket along a vertical line (Fig. 3). Additionally, the bucket during all its way is remaining in a horizontal position.

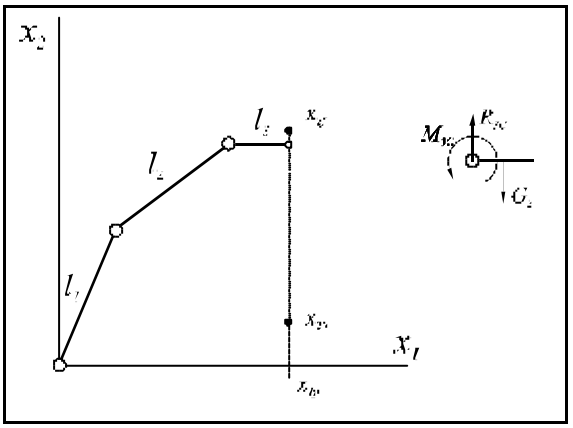

Fig. 3. Bucket motion along vertical line.

We have to find t_f, minimum traveling time from x_{20} to x_{2f}. To make the presentation more clear, all the attachment elements are replaced by straight beams of a constant thickness. We start writing moment equation for the bucket. Due the fact that the motion is planar and that the bucket remains horizontal, its angular velocity is equal to zero. Substituting in (4) and (5) for :

$$\boldsymbol{r}_0 = \left(x_{1p} - l_3\right)\boldsymbol{i}_1 + x_{2p}\boldsymbol{i}_2; \quad \boldsymbol{r}'_C = \frac{l_3}{2}\boldsymbol{i}_1;$$

$$\dot{\boldsymbol{r}}_0 = x_{2p}\boldsymbol{i}_2; \quad \boldsymbol{r}_C = \left(x_{1p} - \frac{l_3}{2}\right)\boldsymbol{i}_1 + x_{2p}\boldsymbol{i}_2;$$

we get, after transformations, the following moment equation of the third element with respect to O'_3:

$$\ddot{x}_{2p}\left(x_{1p} - \frac{l_3}{2}\right) = -G_3\frac{l_3}{2} + M_{3C};$$
$$-M^0_{3C} \le M_{3C} \le M^0_{3C}$$

or in a dis cretized form

$$x_{2p,k+1} - 2x_{2p,k} + x_{2p,k-1} + \overline{G}_3 - u_{3k} = 0$$

where

$$\overline{G}_3 = G_3\frac{l_3}{\left(2x_{1p} - l_3\right)}; \qquad u_{3k} = \frac{2M_{3Ck}}{2x_{1p} - l_3}$$

Recalling the above discussion about optimality criteria, we come to two distinct equations of motion. The first one for the positive u^0_3 and the second for its negative value:

$$\ddot{x}^{(1)}_{2p} = -\overline{G}_3 + u^0_3; \qquad \ddot{x}^{(2)}_{2p} = -\overline{G}_3 - u^0_3;$$

With boundary conditions (10), velocities for both extreme values of control moments are:

$$\dot{x}^{(1)}_{2p} = \left(-\overline{G}_3 + u^0_3\right)t; \quad \dot{x}^{(1)}_{2p} = \left(\overline{G}_3 t + u^0_3\right)\left(t_f - t\right)$$

The intersection of these two lines gives the control switch time t_s with respect to t_f :

$$t_s = \frac{\overline{G}_3 + u^0_3}{2u^0_3}t_f$$

From the condition that the distance $x_{2f} - x_{20}$ is a sum of distances with $+u^0_3$ and $-u^0_3$ active, we find finally minimum time.

$$t_f = 2\sqrt{\frac{x_{2pf} - x_{2p0}}{B}}$$

where

$$B = \frac{\left(u + \bar{G}_3\right)}{2}\cdot\left[\frac{\bar{G}^2_3 - u^2}{4u^2} + \left(1 - \frac{u + \bar{G}_3}{2u}\right)^2\right]$$

Knowing t_f we can find time dependent motion of the bucket. Its motion equations with respect to the center of mass, recalling that $\dot{a}_3 = 0$ (Fig. 3) are:

$$\frac{G_3}{g}\ddot{x}_{2p} = R_{32} - G_3; \qquad R_{32}\frac{l_3}{2} = M_{3C}$$

Now we can proceed, in the same way, to the second member (arm) shown in Fig.4, and then to the first one (boom). Finally, we verify obtained values of M_{2C} and M_{1C} if they do not exceed their assumed limits M_{2C}^0 and M_{1C}^0. If this is the case, the problem of minimum time is solved. If one, or both, of the moments are larger than their limits, we go back to the bucket, decreasing value of M_{3C}^0. The percent by which we decrease it, is equal to the largest percent of violation of M_{2C}^0 or M_{1C}^0.

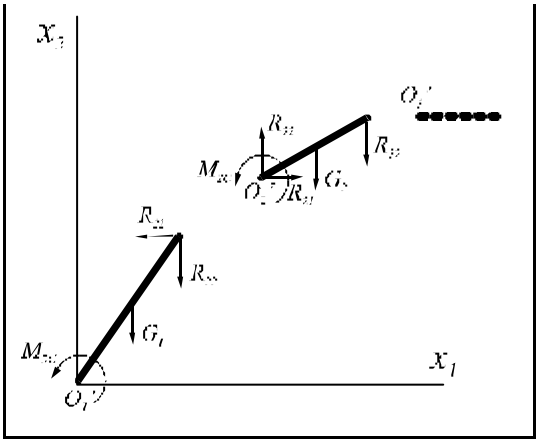

Fig. 4. External forces loading attachment elements.

6. CONCLUSIONS

Minimum time, 3D problems of multibody dynamic system control, with several degrees of freedom and arbitrary constraints, are very complex. Nonlinear state equations, together with constraints, and optimality conditions, constitute a system of equations and inequalities of a very limited value for applications.

In the present study, we propose an approach allowing to decompose the controlled system in separate elements, considering them in a recursive way. This can be applied to bracket kinematic chains. From presented consideration we find minimum time needed to travel of the end effector of the system, along a prescribed path. Beside that, it shown that control moments are taking always their extreme values – positive or negative. The presented relations allow to find the switch time in this ban-bang problem.

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DEVELOPMENT OF A CONSTRUCTION WORK CELL FOR COOPERATIVE LIFT PLANNING

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ABSTRACT: Cooperative crane lifts are considered as an alternative to specialized heavy crane lifts. However, in executing a cooperative crane lift, the precise coordination among the cranes is critical. This level of precision is better assured through automation of the lift operation. However, due to the drawbacks in current crane technology automated execution is not feasible. The development of a prototype work cell for cooperative lifts is addressed in this paper. The prototype manipulator developed has four degrees of freedom and possess the degrees of freedom of a typical hydraulic crane -swinging, luffing, telescoping and hoisting. For programmable control, the manipulator is interfaced to the computer. Uncoordinated motion among the individual manipulators often occurs when subject to cooperative manipulation. The cooperative manipulation is ensured by means of a typical logic that paves the way for proper control flow sequence between the individual controllers through RS-232 serial port. A series of trials were conducted to investigate the behaviour of the system under different cases.

KEYWORDS: Crane lift, Cooperative manipulator, Automated path planning, Computer controlled execution.

1. INTRODUCTION

Safety, productivity and reliability are the three predominant issues facing the construction industry today. Construction work in general is very labor intensive and conducted in situations that are dangerous. It is due to this reason that construction robotics has been a very active research area in the construction industry. Among them, building robots have been employed in various tasks, including material handling and various interior and exterior finishing works. A Local Area Network (LAN) based building maintenance and surveillance robot [1] for maintenance work and for building safety was developed. Applications of robots in hazardous working environment like shotcreting [2], removing lead based paints [3] were developed to replace human operators from harmful effects.

A kinematic control of a pneumatic system by hybrid fuzzy PID was developed [4]. This control algorithm has the capability to position the piston at any desired point in the entire stroke length of the cylinder. Hydraulic large range robots for construction application many a times result in extreme non-linearity. Suitable control methods based on model based dynamic response of the system for position controls are discussed [5]. An automated path planning of cooperative crane lifts using co-evolutionary genetic algorithm was discussed [6]. The issues were focused at developing an automated path-planning procedure for cooperative lift planning using genetic search procedures. The manual operator did the planned lift execution.

The risk associated with cooperative lift execution is much higher than that of a single crane lift due to the interaction among cooperative cranes [7]. In summary, the risks associated with cooperative crane lifts can be categorized into (1) Risk of human error in preparing lift plans and (2) Risk of uncoordinated motion during the lift plan execution. These risks can be overcome by (i) Automating the planning tasks using computer aided planning tools and (ii) Automating lift plan execution using suitable control systems to ensure coordination among cranes.

This paper address the second issue i.e. risk of uncoordinated motion during the lift plan execution. The risk factor associated with uncoordinated motion can be eliminated by means retrofitting the existing cranes with technology for programmable control and automating the lift execution using suitable control systems. Towards this objective, a prototype cooperative manipulator system is developed. The prototype manipulator is an electrically controlled arm model for pick and place operation. The cooperative manipulator system can be programmed to follow the desired trajectory for collision free movement of the object from pick to place location.

2. MOTION PLANNING SEQUENCE

Fig. 2 illustrates the components of a program that automatically generates collision free motions for the cooperative manipulator system. Collision free motion planning relies on three dimensional (3D) information about the physical structure of the robot as well as the workspace in which the robot has to operate. So, the first step in collision free motion planning is the 3D *world description acquisition*. This contains information about the kinematic structure of the manipulator system, obstacles in the work environment and their 3D information such as position and orientation along with details of the lift object.

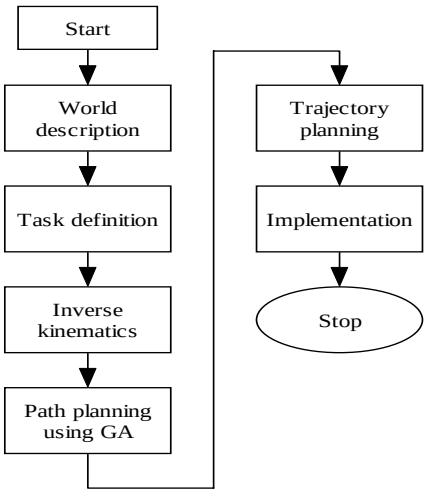


Fig. 2. Program flow control

The *task definition phase* defines the overall task of the manipulator system i.e. defining the desired Cartesian pick point and place point. The *inverse manipulator kinematic* deal with the computation of the set of joint angles and linear translations for the arms that will set the hook point or the end effector at the defined Cartesian pick point or place point. The path planner uses this information and employs a search technique to find a collision free path from the start configuration of the manipulator system to its goal configuration. The trajectory planner converts the collision free path into a trajectory that can be executed by the manipulator i.e. the trajectory planner produces motion commands for the servomechanism of the manipulator. These commands are executed during the implementation phase.

3. PATH PLANNING

A collision free path planner essentially consists of two important components: a search algorithm and collision detection algorithm. The search algorithm explores the search space for optimum movement of the manipulator system from pick to place location. As the search progresses, the collision detection algorithm checks the feasibility of each step movement i.e. intermediate configuration's feasibility in the search space. It checks for collision of the manipulator system with other structural components in the workspace of the robot. A schematic figure representing the workspace along with the manipulator system is shown in Fig. 3a. **T**he planned path is shown in Fig. 3b.

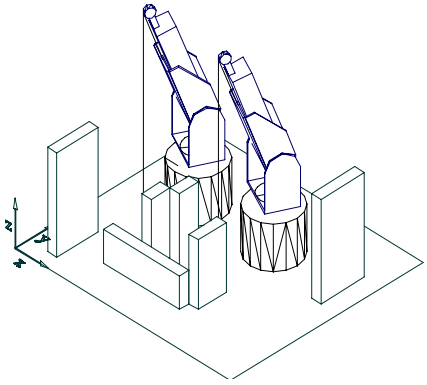


Fig. 3a. Schematic of the workspace

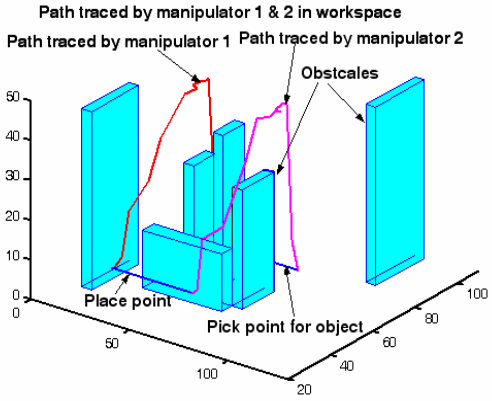


Fig. 3b. Schematic of the planned path

4. MOTION PLANNING

In Fig. 4a, a functional model of a manipulator system is shown. It is a 4 DOF manipulator with two revolute joints and two prismatic joints. The manipulator's specifications are given in Table 1 and the schematic diagram is shown in Fig. 4b. The main column along with other links can rotate around a fixed base on roller bearings. According to crane terminology, it is referred as base and its DOF is named as swinging. The second link is named as boom and its DOF is referred as luffing. The third link is called as extended boom and its DOF is referred as telescoping. The fourth link is the flexible rope that usually gets wound on a drum placed at the end of the third link. The drum is rotated by

servomotor. The link is referred as hoist rope and DOF is called as hoisting.

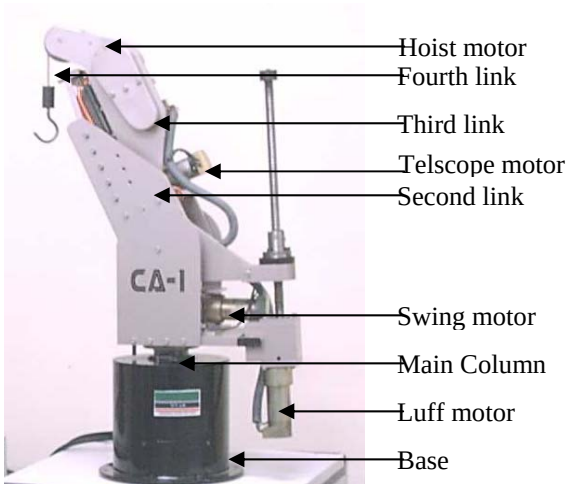


Fig. 4a. Functional model of a manipulator System

Configuration	Revolute type
Axes of freedom	4
Pay Load	10 kg
Base-Swinging	360^0
Boom-Luffing	80^0
Telescoping	150 mm
Hoisting Height	Depends on Luffing Angle of Boom, Telescoping and geometry of Load

Table 1. Manipulator's specification

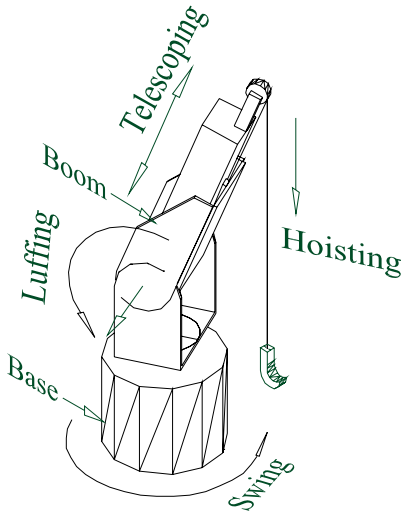


Fig. 4b. Schematic of the manipulator system

For attaching the load, the hoist rope end is provided with a hook arrangement. The manipulator system has repeatability of ±0.3mm for all the links. The manipulator has hardware stop position also called as home position and acts as the manipulator's reference point of move for individual axes.

5. KINEMATIC CONTROL

A block diagram of the overall system is shown in Fig. 5a. To accomplish a kinematic control of a manipulator system, the following considerations are required:

1 Designing an interface unit to convert the supplied data to a form that can be interpreted by the control unit
2 Developing a control algorithm and programming the control unit for position control of the manipulator links
3 Drive unit design in order to amplify output signal from the controller unit to drive the manipulator links.
4 Position sensing unit in the form of encoder; sense the actual positional move and send information to the control unit for proper corrective action.

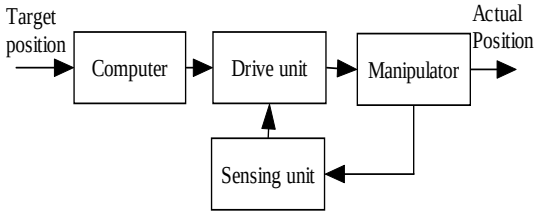


Fig. 5. Block diagram of the overall kinematic control

6. TASK SEQUENCE IN MOTION CONTROL

Fig. 6a represents the controller connection. In Fig. 6b, a flow chart representing the motion control sequence is shown. The manipulator is controlled from a host computer through a host processor, which in turn connects to a programmable multi-axes controller (PMAC) card. The PMAC is interfaced to the servo-drives, which in turn activates the motor. The motor actuation results in link displacement. The encoder sends the actual position feed back to the motion chip where corrective action will be taken.

The manipulator *initializes* the links by making all of them to return to their home position. The *user interface* dialog box written in C++ resides in the host computer. The user enters the desired link position data into the interface unit. The motor used

is a servomotor, therefore the position data is then converted to the required pulse width modulated (PWM) counts for driving the motor.

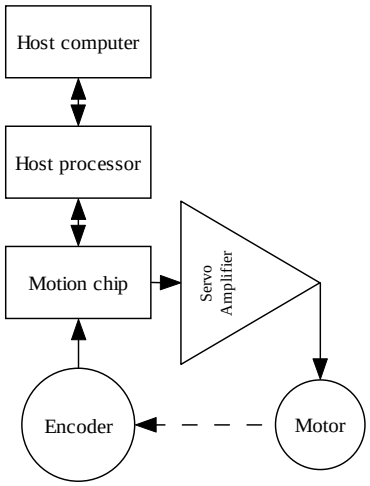


Fig. 6a. Block diagram for controller Connection

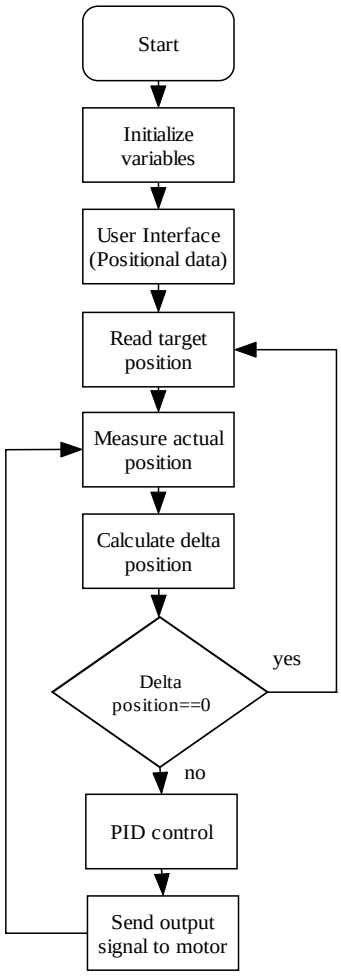


Fig. 6b. A flow chart representing the motion control sequence

The PWM counts required for one complete revolution of respective links varies depend on the servomotor used and the kinematic structure of the link. The equation for calculating the PWM counts is given in the equation 6a:

$$(PWC_c) = (N_2)(N_1)(CPR)\left(T_2 / T_1\right) \qquad (6a)$$

where:
PWC_c is PWM counts required for desired rotation of driven gear (N_2), N_1 is number of revolutions of the driver gear, N_2 is number of revolutions of the driven gear, CPR is encoder counts per revolution of the driver gear, T_1 is number of tooth on the driver gear and T_2 is number of tooth on the driven gear.

Actual position is measured in the form of digital signal, by the *encoder*, which is present as an integral part of the motor shaft. The *control unit* then compares the actual position with the desired position and determines position difference. This difference has to adjust towards zero. A *proportional-plus-integral-plus-derivative (PID)* control algorithm is used to control the motor, responsible for desired link displacement. The PID control algorithm provides a full digital lead compensation for closed loop system stability and the motor command is the output. The compensation D(z) has the form as shown in the *equation 6b*:

$$D(z) = \frac{k\left(z - \frac{A}{256}\right)}{4\left(z + \frac{B}{256}\right)} \qquad (6b)$$

where:
z is digital domain operator, K is digital filter gain, A is digital filter zero and B is digital filter pole.

The compensation is first order lead filter which in combination with the sample timer T affects the dynamic step response and stability of the control system. The sample timer, T, determines the rate at which the control algorithm gets executed. All parameters A, B, K and T are 8 bit scalars.

The digital filter uses previously sampled data to calculate D(z) as shown in *equation 6c*.

$$MC_n = \left(\frac{K}{4}\right)(X_n) - \left[\left(\frac{A}{256}\right)\left(\frac{K}{4}\right)(X_{n-1}) + (MC_{n-1})\left(\frac{B}{256}\right)\right] \qquad (6c)$$

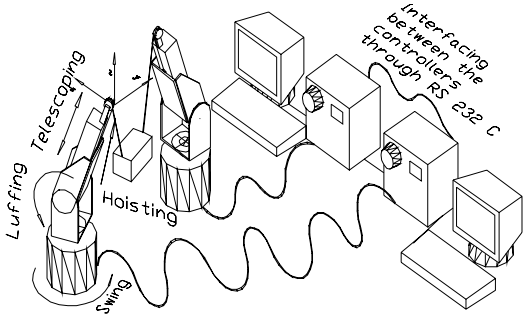
where:
n is current sample time, n-1 is previous sample time, MC_n is motor command output at n, MC_{n-1} is motor command output at n-1, X_n is (command position-

actual position) at n and X_{n-1} is (command position-actual position) at n-1

The motor command output is then sent to the PWM port. The PWM port outputs the motor command as a pulse width modulated signal with the correct sign of polarity. The control process is repeated until the link reaches the acceptable target position.

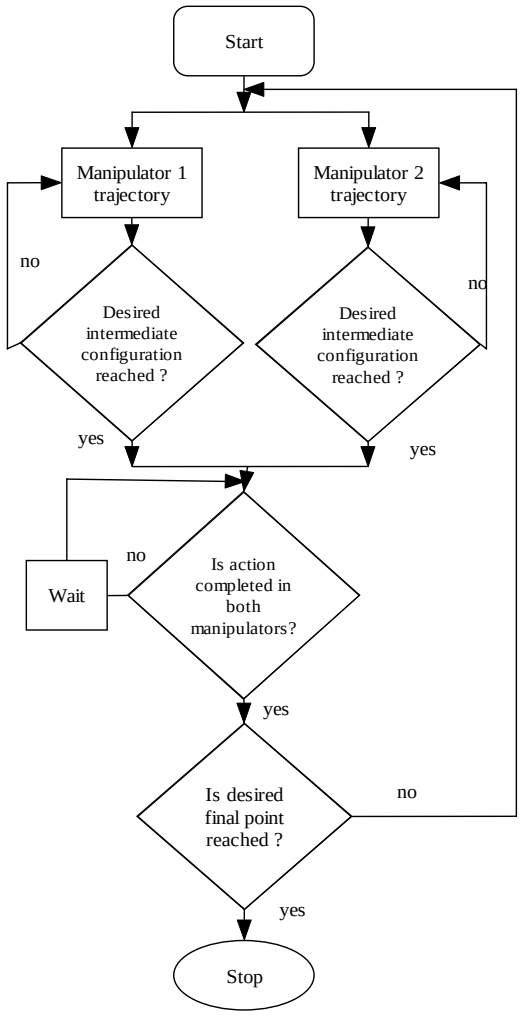
7. COOPERATIVE MANIPULATOR CONTROL

The schematic diagram of the cooperative manipulator system is shown in Fig. 7a and a flow chart representing the cooperative control is shown in Fig. 7b. Cooperative manipulation of the object from pick to place position is ensured only when manipulator 1 and manipulator 2 follow their prescribed trajectories in proper time domain. These trajectories have same number of intermediate configurations between pick and place location.



7a. Schematic diagram of the cooperative manipulator system

Although both manipulator systems are identical, they are found to have different mechanical and electrical characteristics. This results in execution time delay between the manipulators when they are operated independently to follow their prescribed trajectories. For example, manipulator 1 may be at its second intermediate point in its trajectory whereas manipulator 2 could have traveled to the third intermediate point in its trajectory. This leads to uncoordinated motion between the manipulators. This has necessitated the need to control these manipulators for cooperative manipulation. This is possible through RS232 serial port communication between the controllers i.e. controller 1 and controller 2 communicate between themselves through RS 232. Communication between the controllers results in knowing the status of first controller by the second and vice-versa.
A typical logic, constructed inside the controllers initiates the new task only when the previous task assigned to the controllers were executed i.e. both manipulators had reached their same intermediate point.



7b. Flow chart representing cooperative control

This aids in proper coordination among the manipulators for following their prescribed trajectories in proper time domain for achieving cooperative manipulation.

8. RESULTS

Once the collision free path is planned, the planned path is converted to the respective trajectory profile. Using a PID control algorithm, appropriate motor command outputs are generated with respect to time domain and sent to the motor for proper motion execution.

The cooperative manipulation between the manipulators is ensured by means of a typical logic that paves the way for proper control flow sequence among the independent controllers through RS-232 serial port. This results in coordinated motion between the independent manipulators. Snapshots of the collision free motion execution by the manipulator system through the workspace are presented in **Figs. 8(a)-(d).**

The cooperative manipulator system picks up the object, hoist the object over the obstacles, moves progressively over the constrained space, hoist down and place the object on the desired location.

Fig. 8a. Pick location

Fig. 8b. 5th Intermediate location

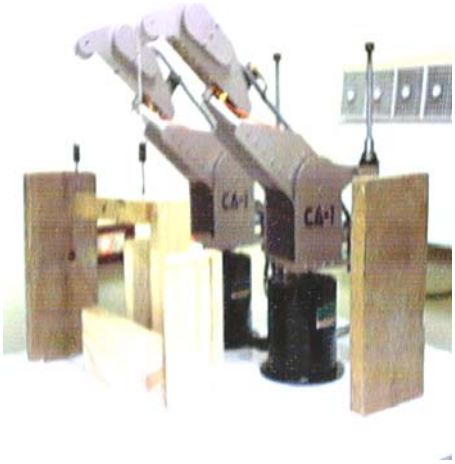


Fig. 8c. 14thIntermediate location

Fig. 8d. Place location

9. CONCLUSION

The objectives of this study were achieved by designing a crane manipulator and controlling it through computer control, for flexible heavy lift applications. The movement of the manipulator system was controlled to move to any desired point within its workspace boundary. All the associated function with heavy lift operation like planning and execution is completely automated. The user has to enter the pick point and place point for the cooperative manipulator system in the user interface module. The executable search algorithm starts generating the collision free path. The collision free path configurations are then converted to the desired trajectories and fed to the respective control unit for desired moves in the workspace environment. The full scale development of this protype heavy lift system can reduce the risks associated with manual execution of cooperative lifts. .

Acknowledgements

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PROCEDURE FOR THE IMPLEMENTATION OF AUTONOMOUS MOBILE ROBOTS ON THE CONSTRUCTION SITE

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ABSTRACT: The implementation of industrial robots in construction industry has proven to be difficult. The problem is not the technique but rather the difficulties in mixing human and robot labour in the dynamic, unstructured environment on site. Both systems need their specific basic conditions, which are impossible to provide on the construction site at the same time.
Now, on account of this, a new procedure for an extensively automated interior finishing work should be described:
Based on a recently developed autonomous mobile robot for drilling and mounting in concrete ceilings, a family of robots was identified to provide at least 80 percent of interior works: Three working units, which are modular designed, have different purposes: 1.Transport the elements from the remote store to the place of assembly. 2.Drill and prepare connections in the building shell. 3.Position and assemble the prefabricated building-elements.
An appropriate procedure was described and simulated by the example of an office building construction. Calculations were compared with conventional building methods to estimate the system's effectiveness.

KEYWORDS: Assembly Robots, (On Site-) Automation, Autonomous, Man/Machine Systems, Process Automation, Simulation

4. INTRODUCTION

A high degree of automation and integration of different production levels has already been achieved in industrial manufacturing by the application of microelectronics and intelligent control systems. In the construction industry, however, this development is so far limited to computer aided planning (e.g. Computer aided architectural design, 3D modelling, calculation of costs and quantities, preparation of project specifications for contract award, structural calculations, etc.). Industrial automated processes are only implemented in the production of components in stationary prefabrication plants (e.g. masonry and concrete elements) in order to obtain high-quality results [3].

But there is a high demand for such solutions: The Institute for Social Research estimates an additional market in Germany of approx. 1.2 million individuals willing to invest in residential housing if the object costs were reduced from currently 250,000 Euros down to about 150,000 Euros. Of course the enormously high plot prices contribute to this situation, but construction costs alone still have a share of approx. 50% of the total costs. Hence strategies within this area need to be developed.
First of all the value adding processes should be transferred from the building site into the fabrication plant: The continuing development of modular and prefabricated systems has a strong impact here.

The conventional building construction on site represents the largest potentials for cost and time reduc-

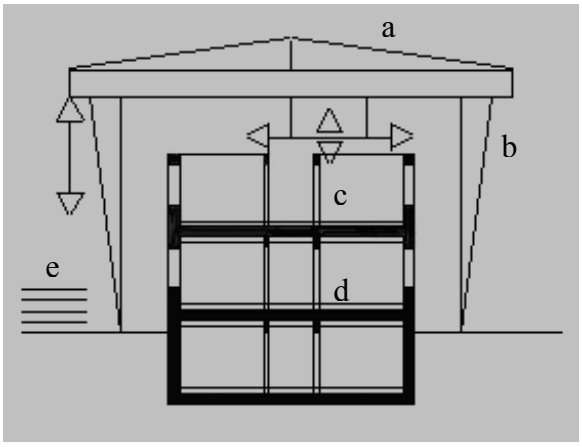
tions as well as potentials for new technologies in the area of automation.
Irregular demand, great variety and high capital costs in construction require similar strategies as already applied in the manufacturing industry. The shorter the time span between contract signing and utilization of the building the cheaper the financing of the project. As a result robot oriented manufacturing requires standardized planning, production and assembly systems [1].
Systems for these applications have been developed for several years, but they have not yet become generally accepted on the market.

5. GENERAL METHODS FOR AUTOMATIC ASSEMBLY OF INTERIOR ELEMENTS

A look at many different existing approaches of assembly processes on-site shows two general procedures:

5.1. Assembly from Outside and Vertically

In this method all construction elements (both structural and light interior systems) are brought in by crane or gantry crane systems from outside and above. The whole working area has to be protected by some kind of roofing during the construction period, because interior building elements are susceptible to weather influences.



Legend:

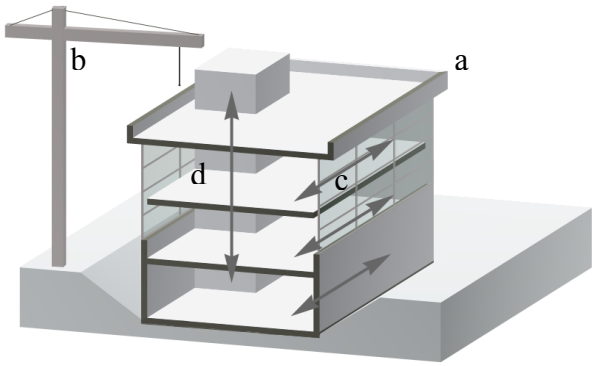
a) temporary roofage
b) (gantry) crane system
c) level in assembly
d) level(s) already assembled
e) bin location

Figure 1. Assembly from outside/vertical, cross section

The advantage of this method is the possibility to handle heavy and big building elements. Gantry crane systems are able to provide a high degree of positioning precision.
On the other hand this technology needs high investment costs, what means that it will be used only in huge projects by large companies.

5.2. Assembly from Inside and Horizontally

This method of automatic assembly is much closer to common procedures on-site. At first the shell is produced (no matter whether in a common or in a more advanced way with prefabricated structural elements). After finishing the curtain wall and the roofing, the horizontal assembly of interior elements with small and light units can be done.
The disadvantage of this technique is that the shell determines weights and dimensions of all working systems. In consequence the prefabricated elements have to be divided into smaller units. Their handling and positioning is more complicated and, hence there is a high demand on organisation and logistics on site. Consequently this leads to a high complexity of all assembly systems.



Legend:

a) building shell, rain proofing
b) crane system (shell construction)
c) Horizontal transport of elements and horizontal direction of assembly
d) elevator for vertical transport of robots and building elements

Figure 2. Assembly from inside/horizontal

On the other hand this procedure is much closer to common organisation structures on site. In addition it can be used by several contractors and requires a lower financial investment. That is why the implementation of systems, based on this second method will be more likely in the near future.

6. MOBILE AND AUTONOMOUS ROBOT FOR DRILLING AND FIXING

In the context of a research project, engineers from the university of Erlangen- Nürnberg and Baumann GmbH developed a robot for drilling and mounting attachments to concrete ceiling slabs. The substantial characteristics are:
The processing unit for ceiling attachment is mounted on a transportation unit.
"It was decided to use a track vehicle as transportation module because of the multitude of obstacles on the floor. Navigation is realized by an image processing system mounted on the transportation module detecting a chalk line, which had been applied manually on the floor. So the machine is able to follow the line and to detect the marked points of operation. As soon as an operating point arrives in the camera's field of vision, the vehicle is slowing down and stops. Then the deviation into x and y direction is determined. Additionally the inclination of the vehicle is measured and the deviation of the tool axle due to it is calculated. By NC-axles in x and y direction these deviations are corrected ".[4]
The travel on-site and the change from one chalk line to another is controlled by a joystick. At the point of operation the process module drills the hole into the concrete ceiling, subsequently fixes a pin or a dowel and assembles the suspension rod for a suspended ceiling system.
In order to perform these tasks the prototype comprises of several lifting mechanisms, a conventional hammer drill, and a conventional device for fixing bolts. Sensor technology and computer control ensure the fine positioning and the perpendicular transfer of the point of operation from the soil to the ceiling [2].

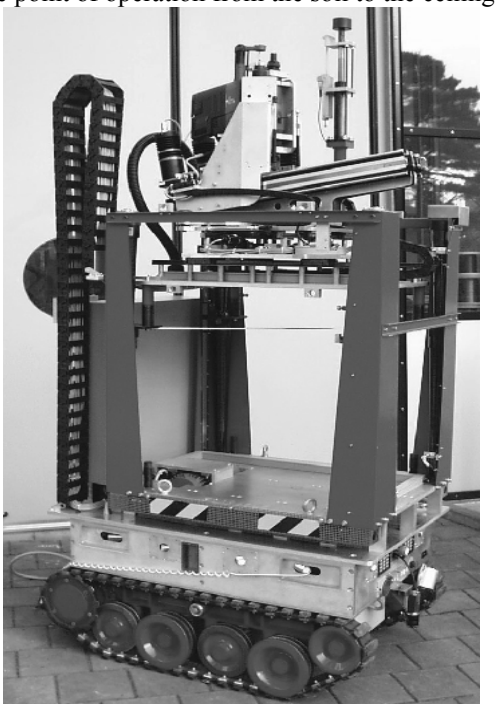


Figure 3. Prototype of a mobile robot system

On-site tests of the robot revealed several obstacles for an efficient application in common project organisation: First of all the problems of mixing human and robot labour in an inconstant, indefinite environment became evident. Both systems require their specific basic conditions, which can not be provided on the construction site together.

Now, on account of this, a new process for an extensively automated interior finishing work needed to be designed. The degree of automation in interior assembly should be increased to approximately 80%.

7. MODULAR ROBOT SYSTEM FOR INTERIOR ASSEMBLY ON-SITE

The decision from an early state of the project to design the prototype as a modular system, were now proved to be right. The flexible carrier unit, is able to transport alternative processing modules for different assembly operations.
Three modules were identified to be necessary and sufficient to provide the aspired high degree of automation:

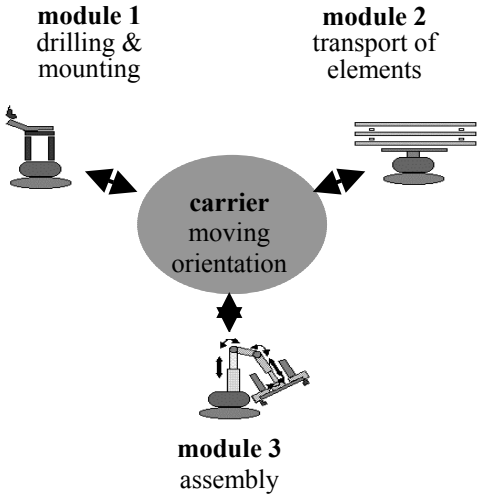


Figure 4. Robot family for a complete interior work on-site
The processing modules perform different tasks: 1.Transport the building elements from remote store to the place of assembly. 2.Drill holes and prepare connections in the building shell. 3.Position and assemble the prefabricated building elements.

4. EXTENSIVE ROBOTIC INTERIOR ASSEMBLY ON-SITE

4.1. Procedure Design

The scenario of the construction of an office building was chosen to develop a procedure for extensive robotic interior assembly on-site.
This application was selected because today it already provides a high level of standards in processes and building systems. In addition to that, there is a high average rate of tenant changes, therefore an often need for reconstruction (every 5-8 years). A technology which considerably shortens on-site construction time in reconstruction is most effective because it minimises losses of rent.

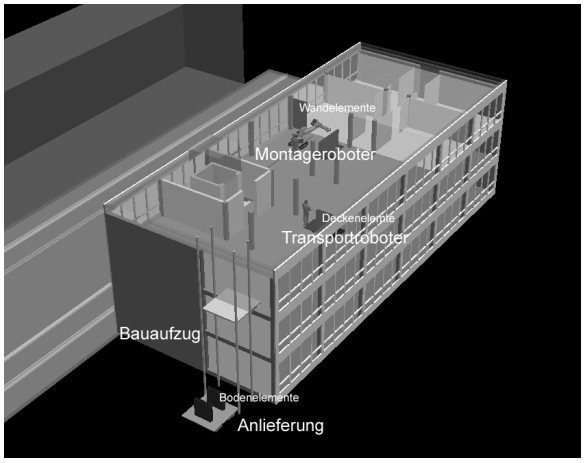


Figure 5. Simulation: "interior robots in office building"; overview

The procedure begins with the mounting robot's work (as described before). It has to prepare all attachments for interior fittings in the hard concrete shell. Afterwards an (external or internal) elevator is allowed to begin with the transport of prefabricated building elements from a remote storage area to the floor of assembly. This elevator also relocates the robots from one level to the other.

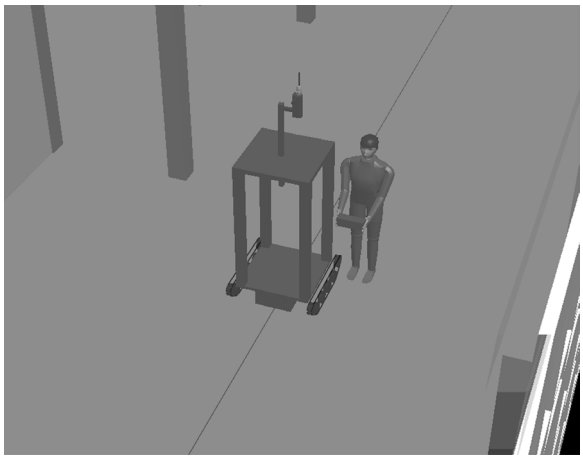


Figure 6. Simulation: "interior robots in office building"; mounting unit

A platform transfers the elements to the transportation unit, which takes over the horizontal transport under manual control. In addition to the carrier this device consists of a turnable and tiltable platform as processing module.

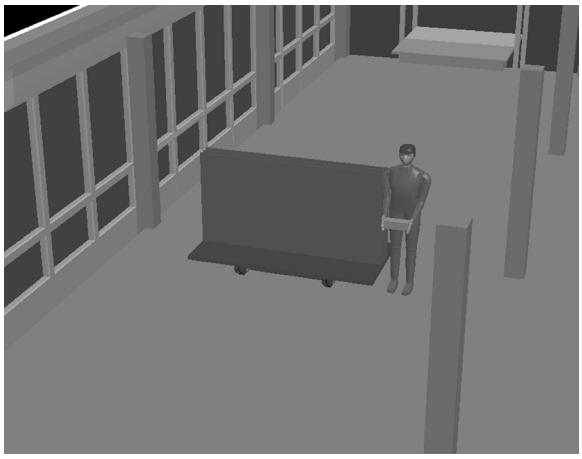


Figure 7. Simulation "interior robots in office building", transport unit

Through a second transfer table the elements are handed over to the assembly device.
This unit is vital for the new procedure: It has to take over the different elements like ceiling panels, walls or floor plates with a vacuum gripper. After that the robot does the fine positioning and fixing of each element.

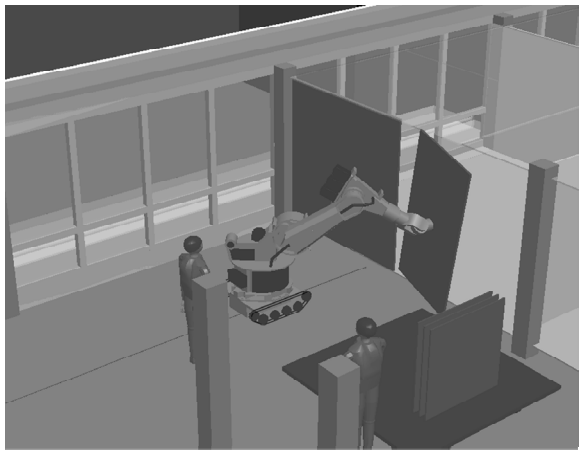


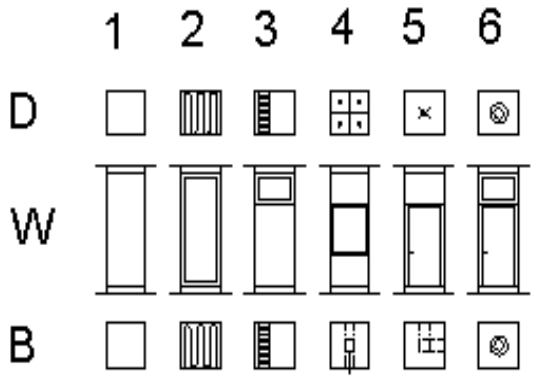
Figure 8. Simulation: "interior robots in office building"; assembly unit

4.2. Robot Design

A special task is to balance the weight of building elements and the lifting capacity of the robot with the weight of the machine, because it is necessary not to increase the common load capacity of the ceiling construction. It will be essential to develop a special lightweight unit. Common industrial robots are not capable to achieve this. Due to the low positioning accuracy of the vehicle, fine location detection is required, which takes a long time. In order to be more efficient it is necessary to provide an ample work envelope which allows to assemble several elements from one position. The simulation showed that it is well possible to assemble three ceiling and three floor elements up to the size of 1250mm to 600mm and three wall plates with a width of 1250m and a height of 3500mm.

It is also necessary to develop a system of interior building elements which is adequate to the automated assembly. In addition its parts have to be flexible and reusable. The focus has to be on how to produce them tailor made and customer driven while cost-effective. The level of prefabrication is vital for the degree of the rationalisation these building elements can reach.

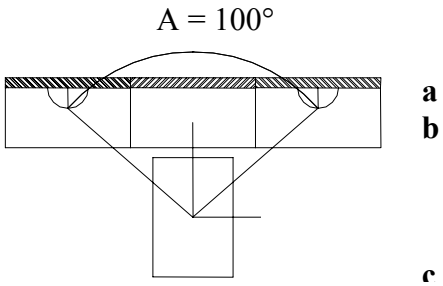
For the scenario a catalogue of necessary building elements, respecting all functional needs and modular ordered was defined. The elements were prepared to fit into a later robot oriented design (ROD).



Legend:
D= Ceiling elements 1: surface only, different materials; 2: heating and cooling elements; 3: Element with different lights 4: Lightning ceiling 5: elements with installations e.g. sprinklers 6: ventilation element. W = Wall elements: 1: surface only, different materials 2: glazed elements 3: with top light 4: with window 5 with door 6: with door and top light B = Floor elements:1: surface only, different materials, 2: heating or cooling elements 3. with radiator 4: with electric interface 5: with electric line 6: ventilation elements.

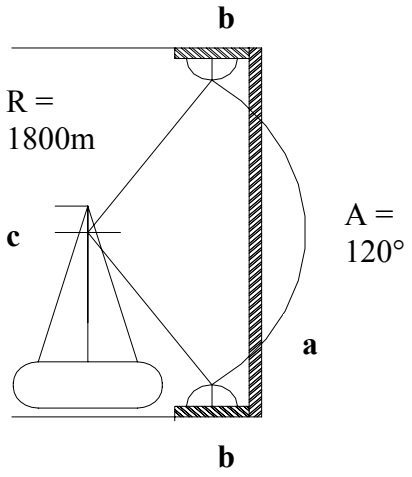
Figure 9. Catalogue of modular prefabricated building elements

The wall element W 6 determines the payload of the machine, which will be approximately 150kg.



Legend:
A wall elements (H 3500, B 1250, T 100)
B ceiling or floor elements (1250/600mm)
C Assembly unit (B_{max} = 850mm)

Figure 10. Assembly unit in standard assembly dis-



position, horizontal section

Legend:
A wall elements (H 3500, B 1250, T 100)
B ceiling or floor elements (1250/600mm)
C Assembly unit (H_{max} = 1900mm)

Figure 11. Assembly unit in standard assembly disposition, vertical section

Taking all calculations into account, the assembly unit has to fulfil the following basic requests:

Maximum total distributed load
(Carrier + processing module
+ gripper) 1100 kg
Maximum dimension (during driving modus)

	B 850mm, L 1500mm, H 1900mm
Minimum Payload (incl. Gripper)	150kg
Repeatability	±1,5mm
Work envelope	horiz. R1650mm
	> 100°
	vert. R 1800mm
	> 120°
Average speed with payload	30mm/s

5. CONCLUSIONS

The simulation of an entire construction process with the new method, gave also information about time expenditure and the number and qualification of staff needed:

o The time of production and on-site construction could be reduced at least by 50% in comparison to the duration of a common project.

o Only one third of commonly needed staff is necessary with the new procedure. But it will demand increasing efforts in project planning, process planning and logistics.

o The staffs on site have to be more educated and specialized as usual.

In consequence the issue will be to reduce considerably unqualified and mostly non-ergonomic work on site and increase the number of highly qualified employees in human working conditions.

The new procedure could generate a higher quality of buildings and processes. Nowadays the chaos on site is proverbial and not only workers and contractors, but also the construction managers have to face a lot of sickening stress factors. The method of work by interior robots is able to obtain well-regulated structures and processes and therefore will achieve a better project outcome for all involved project partners.

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VALUE CREATION BY AUTOMATION AND ROBOTICS IN CONSTRUCTION: AN INTRODUCTION

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Abstract: In the decades to come, building production will concentrate in the metropolitan centres of the world due to the migration of the world's population to the major cities.
An improvement of the construction process in densely populated inner cities will be the task of the future. This focuses on performance management, construction engineering and construction management. New developments being discussed in this field are new design strategies, human machine technologies, employee safety, progress monitoring, distributed production information and Personal Digital Assistants (PDAs).

Keywords: value creation, performance management, construction engineering, construction management, automation, metropolis

1 INTRODUCTION

1.1 The building industry tomorrow

Changes in building production are essential if the world of construction is to improve. The changes are also necessary because the next few decades will see an enormous migration into the cities. The forecast is that in 2015, 55% of the world's population will live in the urban areas (see Figure 1). These metropolises (densely populated inner cities with their agglomeration) impose their own requirements on construction management and production systems.

Figure 1: Quota of urban population [9]

Quota of urban population

	1995	2015
Global and total	45%	55%
Developing countries	39%	50%
Industrial countries	75%	80%

Urbanisation

The following developments occur in the Western European construction industry. In Germany, building production has fallen by 35% in five years; in the Netherlands, by 15% in three years. In other countries on the European continent, the construction industry is hesitant. In Britain, the innovation process 'Rethinking Construction' was the prelude to a change in the system. The development of the 'chip' and the 'chip industry' has completely changed society as a whole. The developments in construction in recent decades can also be attributed to these changes.

1.2. Changes in construction

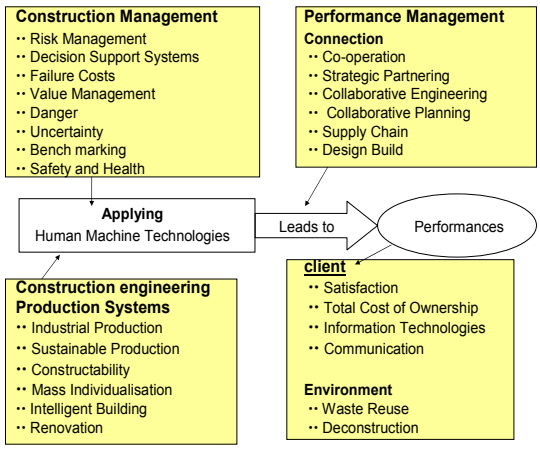
The developments of the construction process are the result of a set of changing circumstances and conditions. These changes encourage developments of technologies to ensure the creation of a process that leads to improved performance for the client. These developments are based on an analysis of the Status Report issued by the CIB Commission TG27 (2001) [1] and of the proceedings of the ISARC 2003 Symposium: The Future Site [2].

In this analysis automation in construction is addressed from the perspective of the performance of building projects serving the client and the environment.

- How can a connection between performance requirements and building production be established and improved through the use of Automation in production?
- How can automation in construction engineering change the role of being a responsible partner in a changing world?
- How can construction management systems contribute to the improvement of production by Automation?

When all building production is ultimately designed to lead to improved performance and a satisfied client, it is always difficult to keep sight of the overall picture and this final goal. Components develop and result in the required performance improvements. The overview in Figure 2 shows the relationship between the various aspects of automation in construction. Construction management, construction engineering and performance management help the managers meet the needs of the client.

Figure 2: Relationship between management, engineering and performance.



1.3.Examples of developments by automation

This paper looks at all three of the following aspects:

1. Performance management with a contribution about the development of new design ideas to meet client requirements in a different way.
2. Construction engineering with a contribution about the improvement of Human Machine Technologies,
and about worker safety on the building site.
3. Construction management with contributions about monitoring project progress,
about collection of the design and management information,
and about support of the work floor manager with PDAs.

We will elaborate on these examples in paragraph 2.

2. DEVELOPMENTS IN AUTOMATION IN CONSTRUCTION

2.1 Automation in performance management. The development of a new design strategy

1. The challenge when building in metropolitan inner cities is the development of production systems that go further than the Automation or robotizing of traditional activities on the building site which are normally carried out on site by construction workers.
A special form of Automation and Robotics is prefabrication. Prefabrication moves work away from the building site to a factory. For construction workers, this is an enormous improvement because working conditions are checked and managed far more effectively. Production is moved to a certain extent but does not really change. However, production only really changes when new processes are developed. Functions are no longer assigned to the traditional building elements and are no longer carried out with those materials that people are used to.

2. Richard's contribution [3] draws an analogy with the development of the printed circuit board. Under the term 'reproduction', he describes an approach that leads to the redesign or re-engineering of the construction process.
"Reproduction implies innovative processes capable of short-cutting the long sequential operations of craftmanship nature - i.e. capable of categorically simplifying the production, as notably illustrated by the analogy of Printing / the Printed-Circuit / the Printed Plumbing Core. Using performance criteria, in order to avoid a captive image from the past, one can identify promising options through the "Technology Matrix" (where processes interact with materials) and thereafter generate building system aiming at Reproduction."
"Reproduction = priority to ideas rather than machinery."
"Reproduction is the introduction of an innovative **technology capable of simplifying the production** of complex goods, of short-cutting long sequential operations. Therefore achieving more substantial economies than mechanizing, automation or robotizing around the traditional construction methods."
"Instead of investing straight into machinery, Reproduction is basically calling upon Research & Development for "ideas" to generate a simplified process. Of course, Reproduction is not necessarily available as a downright option: it is often present together with some of the other degrees industrialization."

3. Richard's contribution gives a whole new dimension to Figure 2. Richard invites us to come up with new ideas. Not for improved production systems with or without the use of automation or robotisation, but new ideas focusing on the performances that ultimately have to be achieved! All these new ideas will have to be generated by a combination of new designs, new forms and new materials that meet the requirements for building in a metropolis. This will create new production systems for the Future Site.

Construction engineering for metropolises (Figure 2) can undergo an enormous impulse. Automation creates the preconditions for following new avenues which will bring us closer to the performance requirements of both client and metropolis. The opposite also applies: without automation, these new ideas cannot be developed into new processes.

2.2. Automation in construction engineering

2.2.1. The importance of Human Machine Technologies

1. The safety regulations for building site work impose more and more restrictions on the loads workers are allowed to carry, prepare and apply using only the resources of their own body. But building contracts will expect an increasing amount of effort. Take high-rise construction in metropolises and the attachment of wall cladding to these buildings, for example. Fitting heavy window panes or attaching wall panels with great precision is a challenge for the robotics industry to come up with new tools for this purpose.

2. The article by Choi (et al.) [7] presents a construction robot that is a hybrid type robot using pneumatic actuator and servo motor. "The hybrid type robot can be used in glass mounting on panel fixing. The hybrid type robot mechanism has a wide range of workspace and precision, and consists of a serial and parallel part. The pneumatic actuator has been widely used in industry site because of its low-cost, compact high rate of power/weight and reliability. The restricting factors preventing the use of pneumatic actuators for accurate control arise from highly non-linear dynamic properties such as air compressibility and friction effects, which combine to severely decrease time responsibility and positioning accuracy. The sliding mode controller is adequate to such as cylinder that is strong non-linear property. The developed construction robot with pneumatic actuator using the sliding mode controller used in the work of an attaching the ceramic tile."

3. With this article, Choi (et al.) make a significant contribution to the development of human machine technologies (see Figure 2) to help in heavy physical work in high-rise construction.
In spite of all the modern production systems, much of the work will continue to be carried out on site. With regard to health, work speed and quality, mechanisation of the work on site will remain an important goal for the successful development of major building assignments in our metropolises.

2.2.2. Worker safety on the building site

1. Complex high-rise construction work in a metropolis is an extremely risky undertaking. Complex logistics on the building site and in full inner cities require construction times to be kept to a minimum. This leads to highly compact building processes and production systems that are sometimes unsafe and create many minor and major risks for the construction workers.

2. "The work described in the article of Abderrahim (et al.) [5] deals with the development of a particular security system, using both existing commercial technology and specially designed equipment. The compulsory safety helmet required for all workers in construction sites is used as the base to accommodate miniature positioning and communication instruments. The position and ID of each worker is sampled periodically and sent via radio to a monitoring station, where the information is compared to a database containing the tasks and processes being performed in the site. According to this, workers and machines' positions are known in each instant and risk situations may be recognised immediately and therefore damage can be prevented. If certain workers and particular machinery and equipment elements are not supposed to be in certain locations for safety reasons, an automated system can be used to detect the situation and make the adequate decision to prevent a possible accident. The proposed system is meant for modern construction systems where workers and automated/semi-automated machines coexist."

3. If we apply the article by Abderrahim (et al.) to Figure 2, we see that it can make an important contribution to the minimisation of risks. The instrument is designed to localise and detect the risks on site that cannot be prevented and to inform construction workers with warning signals of approaching danger (e.g. machines or crane loads) and to prevent people falling into openings in floors.
By using databases, radio signalling and normal radio communication equipment, automation (ICT) can reduce the remaining risks on the building site which cannot be prevented by collaborative engineering of by improving production systems. This makes it an important instrument in the final phase of risk management. The automated system adds value to the development of high-rise building in metropolises by perfecting risk management.

2.3. Automation in Construction Management

2.3.1. Monitoring project progress

1. The complexity of building in a metropolis prompts the inclusion of performance indicators other than the traditional ones in a contract. A traditional contract gives the contractor the responsibility to supply products and to assemble them into a structure, and he is given a certain

amount of time and money to do so. He is also expected to use the necessary capacity in terms of workers and machinery. In the traditional system, the contractor provides a design with drawings and calculations.
The new construction assignment challenges the construction industry to carry out projects under new contract conditions. The newness of these contracts becomes apparent from performance indicators other than the traditional ones. The traditional performance indicators were primarily time, money and a detailed design with materials to be supplied. The new types of contract place responsibility more integrally on the contracting parties.
This supplements the traditional performance indicators with new ones and creates the need for integral monitoring and checks of the project progress.

2. Navon's article [4] describes the options and developments using examples.
"There are also briefly described together with the concept of measuring indirect parameters and converting them into the sought indicators. These are: (1) labor and earthmoving productivity, based on measuring the location of workers, or earthmoving equipment, at regular time intervals. (2) Progres, based on the above data, or data collected from a tower crane. (3) A comprehensive control of construction materials, starting by monitoring orders and purchasing up to the movement of the materials on site. (4) Monitoring the status of guard rails in order to prevent falls from heights."

3. If we apply Navon's contribution to Figure 2, we see that developments in the world of ICT have a positive impact on the development of the possibilities of all kinds of aspects of construction management. They are the tools the contract partners can use to monitor the progress of complex contracts. The automated monitoring system adds value to the development of new types of contracts.

2.3.2. Acquiring design and management information

1. Effective, tight management of projects during the development, design, execution and maintenance phases depends on a great deal of information. Without the right information, management is more like gambling and guessing than informed control. Construction in metropolises entails working with more partners than people are used to. These partners not only work together on the same project, they also need one another because they have their own projects which depend on one another. For example: flats above shops, offices with shops above a railway station. Various owners all have their own interest, backgrounds, needs, requirements, functional specifications, decision-making processes, etc. These aspects each generate their own specific information, so the manager who has to head up integrated projects in a metropolis is confronted by an immense flow of information. This information is not fixed, so the manager also has to rely on the quality of the information he is working with.

2. The article by Van Leeuwen (et al.) [8] discusses this problem and works out a proposal for not distributing this information but for sharing the various information sources.
"The validity of information that a manager obtains from partners in a project can only be guaranteed by sharing of the information resources. This means that, rather than providing a copy of the information, the information is accessed at its source where the provider of the information has full control (and responsibility) over it."
"To achieve such sharing of information, Van Leeuwen (et al.). propose a change of the paradigm 'distributed product information' from the supplier point of view to the consumer point of view. 'Distributed' no longer means 'sent to many clients' but rather 'accessed at many providers.' Sharing distributed information resources has the potential to improve business processes in many ways:
- Avoiding unsolicited communication, the traffic of information is reduced, even if there is an increased amount of wanted traffic;
- It improves the validity of information, because it remains under control of the provider;
- It increases the quality of information, since it can answer a specific request or even result from a, possibly automated, dialogue;
- It helps to integrate business processes by keeping the relationships between the processes and their output data active."

3. In the article, Van Leeuwen (et al.) provide an important insight into the development that ICT can stimulate possibilities for the exercise of construction management (see Figure 2). With the right ICT tools, the manager (the client) has up-to-date information about all production systems, all risks and uncertainties, and all design decisions and design options. This information enables him to follow how plans and production are developing on a daily basis (without lacking information) and how they ultimately meet the requirements of the client. It would probably be impossible to complete these complex construction projects in our metropolises without these kinds of ICT systems.

2.3.3. Support of the work floor manager with PDAs

1. These days, the on-site construction manager has serious problems having building production information processed efficiently, quickly and on time. On complex high-rise or underground construction projects in the metropolises, production information is not only processed to monitor progress

and quality. A lot of data about the vicinity (groundwater level, stability of adjacent buildings, good traffic circulation) has to be processed every day. This is not only required to monitor progress, but also to prevent damage and ambient danger and to minimise risk.

2. The article by Kimoto (et al.)[6]:
"This paper reports a development of mobile computing system with PDA (Personal Digital As sistants) for construction managers on construction sites. First, this paper describes the aim, the concept based on End User Computing, and the essential element of the mobile system. This also shows the necessary functions for the mobile computing, and the concept of this computer-aided engineering system. Secondly, this paper describes the structure of the system and the outline of subsystems: Progress Monitoring System, Inspection System, Checklist and Reference System, and Position Check System".

3. To convert the work of the on-site construction manager into a substantive role and less that of an administrator of important information, it is essential to develop mobile computing systems in accordance with the proposal put forward by Kimoto (et al.).
The reporting process is fully automated from the location in the project where the information is checked or available. Using a mobile computing system in combination with the distributed product information set out by Van Leeuwen (et al.) (see elsewhere in this volume) would cut out a whole series of administrative activities throughout the project and increase the efficiency of data management. All data on the various construction management aspects in Figure 2 are collected integrally and processed in real time.
When this data is linked to pictures from a digital camera and speech recognition in the future, it will be a real help to the construction manager, who will then have more time and attention for the actual content of the project.

3. CONCLUSION

The building assignment will focus on metropolises, which sets specific requirements for performance management, construction management and construction engineering.
Clients need individual treatment and a specific approach designed to solve their problem and meet their demands. They are less concerned in the size of the investment, but are becoming more and more interested in the total cost of ownership and life cycle cost. Nowadays, clients are less concerned with the structure itself. They pay more attention to its functional use, and this primarily stimulated by the use of information and communication technology in the projects.

Design strategies improve performance management.

Construction engineering is changed by the application of more industrial production, sustainable production, mass individualisation, and intelligent building to improve constructability.
Construction management has to deal with safety and health, uncertainty and danger. Developments are taking place in risk management, value management and decision support systems supported by partnering collaborative design, supply chain management.

Better ICT tools provide the manager with better information faster by using distributed systems and PDAs.

These developments demonstrate that there is plenty of room for improvement in all process elements of construction projects in metropolises.

This underscores the economic importance of automation in construction. The ultimate goal is the value creation construction is capable of.

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MULTI-DOF (Degree Of Freedom) CONSTRUCTION ROBOT FOR A CURTAIN WALL INSTALLATION OF A SKYSCRAPER

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Abstract: Recently, the trend in architectural forms has been toward larger and taller building. The building materials, therefore, are getting larger and heavier as well. Typical construction machineries are, however, not adequate for handling these materials and most of the construction works have been still managed by a human operator. Construction processes are, therefore, fraught with a number of problems, including frequent accidents, high construction cost and heterogeneous construction quality; which is depended on the experience of the worker. In various construction sites, automation in construction has been introduced to address these problems. In this paper, the process of a curtain wall construction in the skyscraper is analyzed and proposed the Multi-DOF Construction Robot (MDCR) for this construction process. The need of man power can be reduced by using the proposed MDCR, the construction period and cost can be retrenched as well. The MDCR can be assured safety in the curtain wall construction site. The performance of proposed robot system (MDCR) was verified with the real application test in skyscraper construction site.

Keywords: Curtain wall, Skyscraper, Multi-DOF Construction Robot (MDCR), Modularization, a macro-micro motion manipulator, Human machine cooperative system

1. INTRODUCTION

Recently, the research on robot has a lively progress from the innovative development of high-technology. An industry robot is, therefore, applied widely to a manufacturing field such as an automobile industry [1]. In the same way, the application of construction automation system and robot has been considered to improve productivity and safety in construction industry. Compared with a manufacturing industry, the automation technique has not been applied due to the characteristics of a construction industry [2].

The current trend in building construction is toward taller and larger buildings. The building materials are, therefore, becoming larger and heavier as well. Many of the types of equipment used to handle these materials are outdated, and most of the construction work is managed by a human operator. Construction work is, therefore, fraught with a number of problems, including frequent accidents, high construction cost and heterogeneous construction quality which depend on the experience of the operator [3]. To solve these problems, it is necessary to introduce the construction automation system and robot. Furthermore, humankind has expended its territory. It now reaches into space and under the sea. Construction equipment, therefore, must be developed to handle these new construction challenges [4].

Generally, a construction robot has been developed for higher productivity and better safety in many different areas of construction [5, 6]. As the trend of building construction is changed, the curtain wall to determine a building image is becoming the object of many concern in the constructing a building field. A curtain wall is one of materials for outer wall construction method. It is appropriate for super tall buildings (or skyscraper). For this reason, an automation system and robot for curtain wall

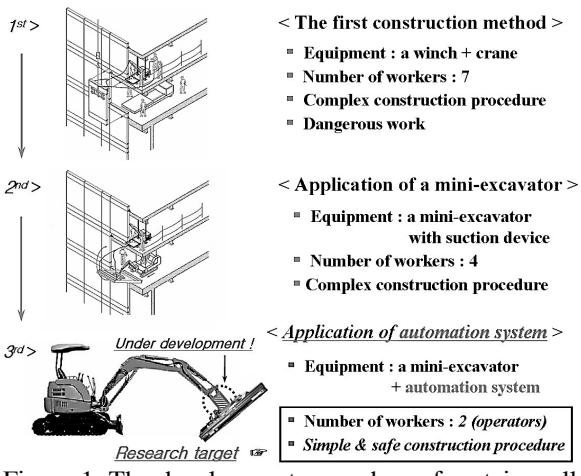


Figure 1. The development procedure of curtain wall installation method

installation in a skyscraper construction procedure must be developed.

Up to now, the development of curtain wall construction is classified into 3 processes such as Figure 1. In the first construction method, a curtain wall is installed using a winch and crane, as well as many workers. Its procedure is complicated and slow; as well, it is dangerous for the workers. In the second construction method, to improve the procedure, a commercial mini excavator with suction device is applied. The suction device has one rotation mechanism which is operated by manual manipulation. Figure 2. shows the suction device.

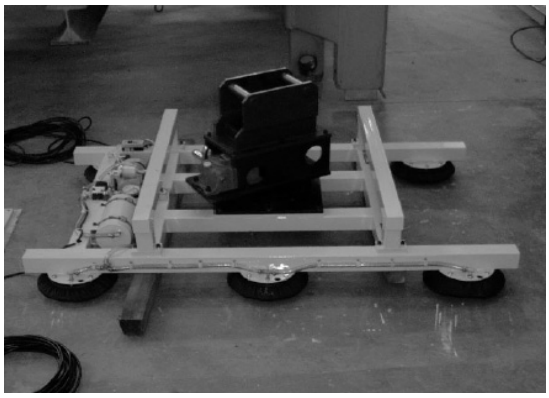


Figure 2. The suction device

Through use of the mini excavator system, a curtain wall can be moved to the assembly point easily. This system also reduces the number of workers and the amount of construction period. The curtain wall assembling, however, must still be operated by a construction worker. The authors of this paper propose a human machine cooperative system which replaces the suction device in the mini excavator system. The system under developing now and it is applied to the third construction method.

This study considered these processes and conceived of a way to employ a robot in the installation of the curtain wall in a skyscraper construction work. The use of robots at construction sites can reduce the need of human involvement. Construction period and cost can be reduced as well. An important aspect of the use of robots at construction sites is prevention of accidents [7, 8].

2. ANALYSIS OF AN EXISTING INTALLATION METHOD; THE MINI EXCAVATOR SYSTEM

The current curtain wall installation method must be analyzed in order to design a robot. The mini excavator system is composed of a suction device and a commercial mini excavator. A suction device holds the curtain wall with a rotation mechanism. An excavator is used to move the curtain wall to the assembly point. Figure 3. shows the mini excavator system.

Figure 3. The mini excavator system

2.1 Definition of a coordinate system of curtain wall

Before analysis of the current curtain wall construction method can be conducted, a coordinate system must be defined as presented in Figure 4. The origin of the coordinate system is located in the center of mass of the curtain wall. T represents translation and R represents rotation.

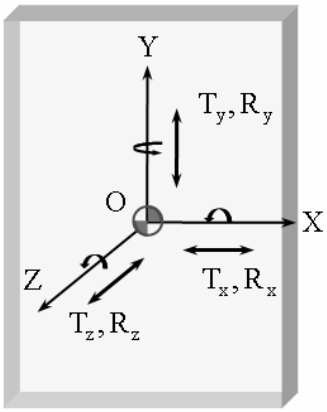


Figure 4. A coordinate system of curtain wall

2.2 Analysis of an existing installation method according to the procedure

2.2.1 Suction

By using the suction device on the end of a mini-excavator, the curtain wall is held in place. The required DOF is R_z to align with the excavator.

Figure 5. The suction process

2.2.2 Movement

The curtain wall is moved toward an assembly point by a mini-excavator. The required DOF are R_z to avoid obstacles.

Figure 6. The movement process

2.2.3 Placement

The position and orientation of a curtain wall is adjusted by a R_z rotation mechanism. The required DOF is T_x, T_y, T_z, R_x, R_y, and R_z. The utilizable DOF in a mini-excavator is T_y, T_z, and R_x. The utilizable DOF in the rotation mechanism is R_z. A residual DOF is handled by a worker.

Figure 7. The placement process

2.2.4 Installation

The mini-excavator is separated from the curtain wall. Then, the final assembly work is executed by a worker. The required DOF is T_x, R_x and R_y.

Figure 8. The installation process

3. A CONCEPTUAL DESIGN OF MULTI-DOF CONSTRUCTION ROBOT

3.1 Determination of essential DOF

In the installation of a curtain wall, the required DOF is T_x, T_y, T_z, R_x, R_y, and R_z. The utilizable DOF in the mini excavator is T_y, T_z, and R_x. Through the experience of install operator, essential DOF in the construction robot is T_x, R_y, and R_z. Under developing system, therefore, has a three-link RPR manipulator such as Figure 9.

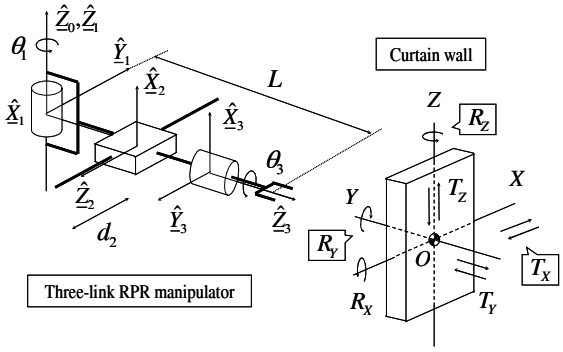


Figure 9. Schematic diagram of a three-link RPR manipulator

3.2 Consideration of overturning

One of the most important considerations at a construction site is the safety of human workers. If an excavator loads over weight, it will be overturned [9]. To prevent overturning, safety tests were considered, as presented in Figure 10.

Figure 10. The overturning test of a mini excavator

When the boom and arm spread parallel with the ground, a heavy material could be lifted up to 500 kg by a commercial mini excavator. The weight of a curtain wall is 300 kg from Table 1. The system under development, therefore, must weigh less than 200 kg. Through the overturning test, the boundary condition of robot design is established, such as table 2. An importance of the establishment of boundary condition in robot design is prevention of accidents and troubles.

Table 1. Specification of curtain wall

Specification	Data
Weight of curtain wall, [*kg*]	300
Width of curtain wall, [*m*]	1.8
Height of curtain wall, [*m*]	3
Thickness of curtain wall, [*m*]	0.2

Table 2. Specification of curtain wall

Design spec.	Data
Total weight, [*kg*]	200
Weight of each module, [*kg*]	50
Weight of suction device, [*kg*]	50
Total length, [*m*]	0.50
Translating velocity, [*m/s*]	0.05
Rotating velocity, [*rad/s*]	0.209 (2 [*rpm*])

3.3 A design of system specification

The system under development can be used not only in curtain wall installation but also in other construction work. This system, therefore, is modularized to add or remove DOF. Table 3. shows the diagram of the modularized design.

Table 3. Schematics of a modularized 3-DOF manipulator

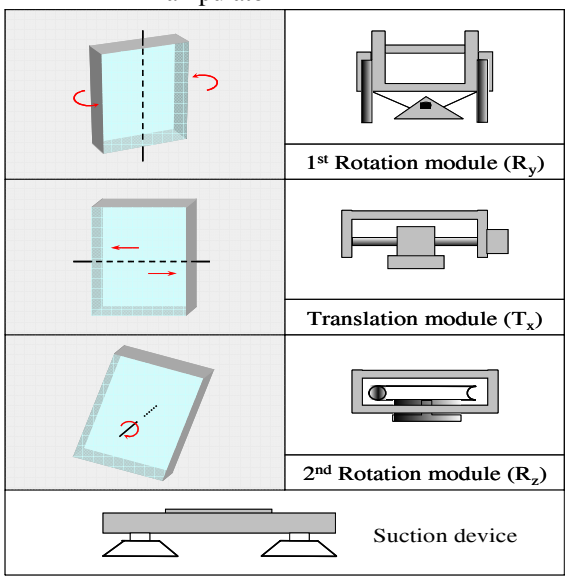


Table 4. Required force and Torque in each module

Module	Data	
1st Rotation(R_y)	Motion Range	±20°
	Required Torque	196.4 [Nm]
Translation(T_x)	Motion Range	±0.25m
	Required Force	20.0[N] (No Friction)
2nd Rotation(R_z)	Motion Range	±270°
	Required Torque	725.54 [Nm]

The specification of each module is determined by analysis of the current curtain wall installation work. In the design of a system, the required torque and force have to be calculated to select the proper actuator, as presented in Table 4. The actuator of each module is selected by comparing AC servo motor with hydraulic motor, such as Table 5.

Table 5. Comparison AC Servo Motor with Hydraulic Motor

	AC Servo Motor	Hydraulic Motor
Actuator	· Easy control · Extra power transmission device · Low accuracy (a reduction gear) · High speed operation	· Hard control · High power · Refrigerator needed · Low speed operation
System	· Simple-wiring · A Cheap unit	· Complex-wiring · A expensive unit · Oil leak

4. REALIAZAION OF THE MULTI-DOF CONSTRUCTION ROBOT

The curtain wall installation system overview is a macro - micro motion manipulator. A mini excavator is considered to be the macro motion manipulator. The system under development is considered to be a micro motion manipulator. Figure 11. shows the micro motion manipulator which is under development.

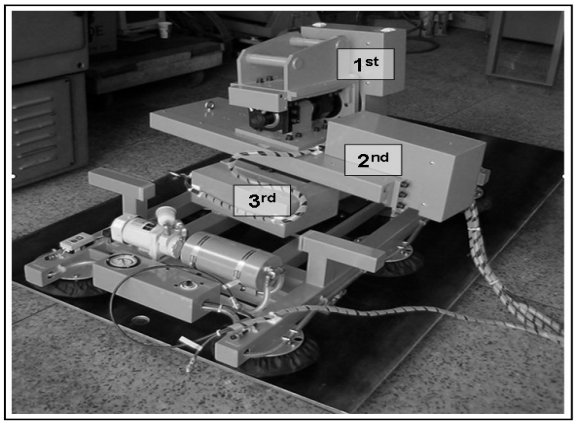


Figure 11. The micro motion manipulator

The arrangement of each module is determined by analyzing of characteristic, such as Table 6. Figure 12. shows the macro-micro motion manipulator.

Table 6. A characteristic of each module

Characteristic	High ⟷ Low		
Frequency of use	3rd	2nd	1st
Durability for a load	1st	2nd	3rd
Moment of Inertia	3rd	1st	2nd

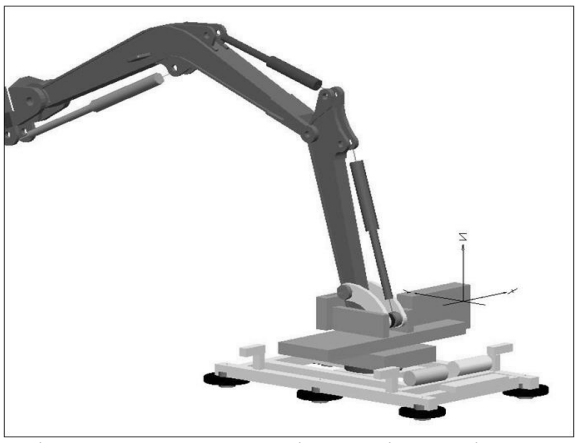


Figure 12. The macro - micro motion manipulator

5. CONTROL STRATEGY

Generally, the fully automated system is not suitable for construction work due to frequently changed construction environments. A human machine cooperative system is, therefore, suitable for construction work [10, 11]. It is an interactive system in order to cooperate with the human, as presented in Figure 13.

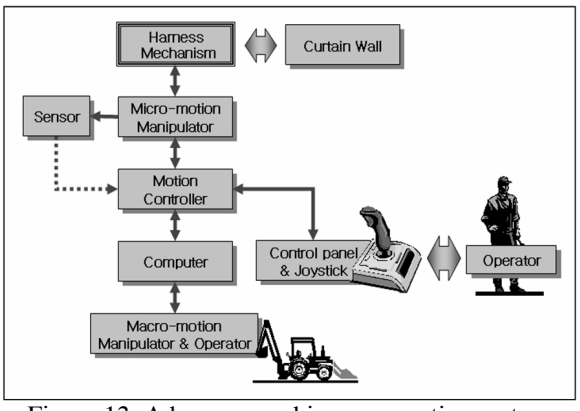
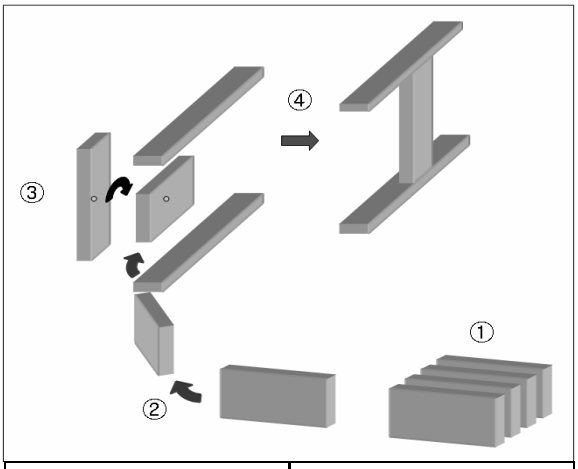


Figure 13. A human machine cooperative system

6. SIMULATION OF INSTALLAION

Before the developing system is applied to the construction site, simulation is needed to estimate goal achievement for a conceptual design, such as Figure 14. Through the simulation of installation, a new installation process is established, as presented in Figure 15.

Figure 14. Simulation of curtain wall installation



① Loaded Curtain-wall	② Moving
③ Rotating	④ Assembly Complete

Figure 15. Schematic diagram of curtain wall installation

7. HUMAN ROBOT INTERACTION

For adequate (or optimal) productive gains, a human should have a minimal capacity or skill level to effectively and efficiently work with the robot system. The job skills and experience, therefore, are defined from a diagram of working process as shown in Figure 16. The operators require more skill and knowledge than the traditional operator.

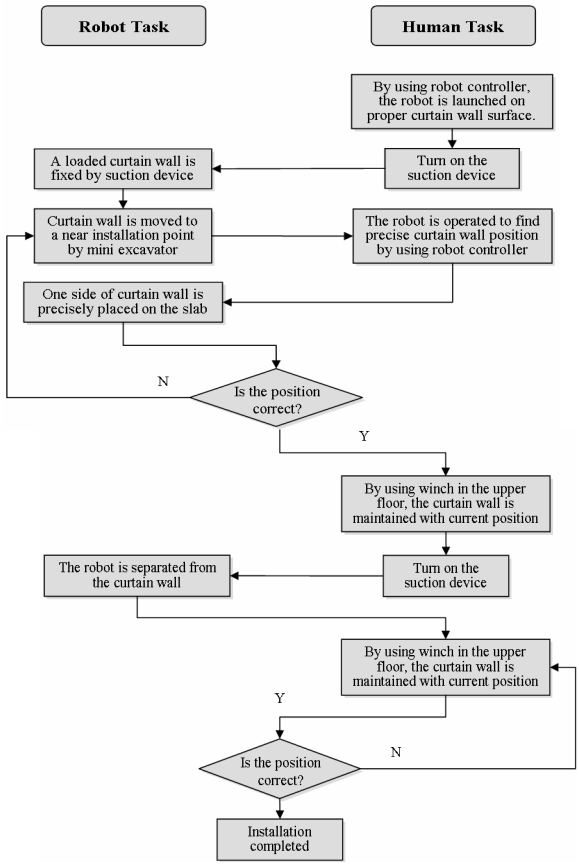


Figure 16. Human robot interaction diagram

8. CONCLUSIONS

The ultimate goal of the proposed system is for human-machine cooperation. The robot is commanded/operated through human force; in turn, it assists the human operators [12].

The system described in the present study is one step on the way to full automation. There is still a long way to go; however, the research and development continues. The advantages of proposed system include the following:

- ✓ Simple and precise construction procedure
- ✓ Reduction of the numbers of human workers
- ✓ Safety assurance
- ✓ Retrenchment of the construction cost and period
- ✓ Homogeneous construction quality

Much of the automation in construction has been developed for outdoor work. The proposed robot is being developed for curtain wall construction work at indoor sites. The micro-motion manipulator is modularized to allow for addition or removal of a DOF. Furthermore, the proposed robot can be applied to other construction work by exchanging the end-effecter.

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ROBOTIC MOUNTING SYSTEM FOR LARGE-PANEL BUILDING

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Abstract: The paper presents the principles of construction and structural organization of the robotic mounting system. The concept of developing models of manipulators with elastic couplings has been suggested in terms of which we have obtained mathematical description of the crane. The problems of constructing mathematical models of the system manipulators interaction have been considered and the technique for calculating moments to control the mounting system has been suggested.

Keywords: construction, large-panel building, mounting, robotization.

1. INTRODUCTION

The promising trend in automation of bearing-wall buildings mounting is the creation of robotic mounting system with interactive and adaptive control. In the process of mounting wall panels there appears the problem of wall panels positioning and retaining panels on the design position during its installation and fixing. Incorporation into the system of the mounting robot makes it possible to mechanize and automate the process of the structures orientation and mounting.

2. PRINCIPLE OF THE MOUNTING SYSTEM ONSTRUCTION

The basis of the mounting system incorporates a tower crane and a positioning robot with a mounted wall panel. The functions are distributed between the crane and the robot in the following way. The crane supplies the panel to the place of mounting and keeps it during the process of mounting and orientation and the positioning robot performs a panel space orientation before mounting. The crane and the robot interaction in the zone of a panel mounting is so organized that the crane doesn't interfere free movement and turning of the plate and the robot ensures positioning and orientation without any significant loads on the manipulating system.
Structural organization of the robotic mounting system is presented in fig. 1. The tower crane being incorporated into the system is equipped with a special automated cross-piece and a system of programmed control (SPC). On the basis of control vector g_c, $\dot{g}_c$ and current position of joint coordinates q_c and joint speed $\dot{q}_c$ the crane control system produces control forces and moments μ_c.
The mounting robot is equipped with two manipulators and a moving platform. The investigations have shown that application of two manipulators ensures a reliable joining with a panel and fulfillment mounting operations at rather small static and dynamic loads on the manipulating system. The mounting robot is equipped with the system of programmed control with elements of adaptation. The main component of the whole system is the data-measuring system, its function is to control position and orientation of the mounted panel and also the reference of the robot platform to the design axes of the erected object. The base of the DMS is the laser set-point devices and photo-matrix transducers located on the cross-piece and on the manipulators' grippers. DMS forms the system state vector x_p on the basis of which the synchronization and control device (SCD) of the upper level performs planning of the system mechanisms movements.

A 3-level control system is implemented in the whole system. The synchronization and control device of the upper level on the basis of the planning algorithms forms control vectors g_r, $\dot{g}_r$ for the robot system control and the vectors g_c, $\dot{g}_c$ for the crane control system. And the vector formation is effected with account of the wind load and elastic deformations. Taking into consideration complexity and responsibility of the system's mechanisms operation, planning of the crane and the robot's movements is carried out on the basis of simulation of the mounting process. The system models used for this purpose are designed taking into account the distribution of functions that are carried out by the

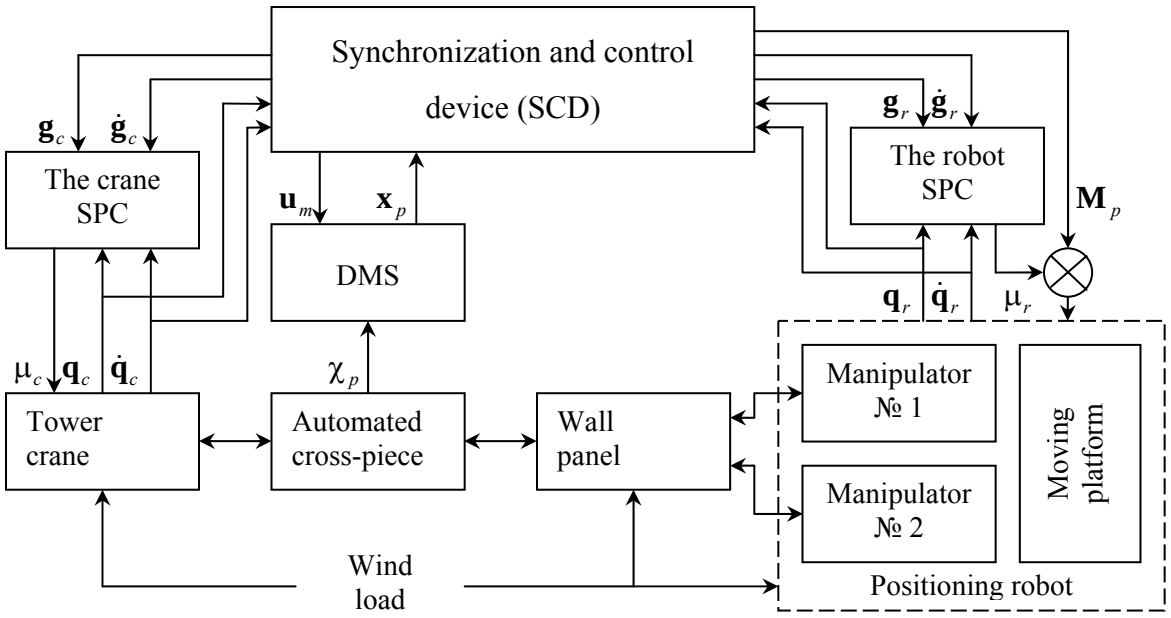


Fig. 1.

crane and the mounting robot. During the process of a panel positioning and mounting strict requirements are not specified to the crane relative to dynamic characteristics and the robot is to provide high accuracy of positioning. Therefore the crane control is realized with the help of kinematic algorithms according to the designed trajectory. The requirements of high accuracy of the mounting robot positioning and a wide range of loads changes of the manipulator drive cause the necessity of applying dynamic control laws for the robot control. Besides on the upper level we calculate the joint moments necessary to overcome the panel resistance M_p; on the medium level – the moments stipulated by the dynamic properties of each manipulator on its own μ_r.

3. ATHEMATICAL MODEL OF THE MOUNTING SYSTEM

A specific feature of developing dynamic model of the robotic system is the availability of branched and closed architectures. So the application of classical methods is connected with certain hardships. When using the modified Lagrange – Euler method the analytical representation of the system becomes awkward and is not convenient for investigation. Application of the Newton method requires finding minimum of functions that is not efficient from the computational point of view and not convenient for analytical investigation. Therefore mathematical model for the mounting system constructed according to the principles of decomposition we have obtained tree autonomous mechanical systems the interaction between which is accounted according to the principle of small motions. The essence of this principle lies in that before the simulation begins the linked bodies are in the state of rest and don't influence each other. Having begun their movement the bodies carry out small motions according to which the displacements are determined. The arising elastic deformation cause reaction forces in each point of the robot attachment:

$$\mathrm{N}^{(k)} = \left(\delta + \gamma \cdot s\right)\left(\mathrm{x}_r^{(k)} - \mathrm{x}_c^{(k)}\right),\ k = \overline{1,l},$$
$$s \equiv d/dt \qquad (1)$$

where δ, γ are the coefficients of stiffness and connection dissipation; $\mathrm{x}_r^{(k)}$, $\mathrm{x}_c^{(k)}$ are the vectors (3×1) of Cartesian coordinates of the *k*-th suction cup and the places of this attachment.

Therefore the model of the mounting system consists of 3 channels simulating the dynamics of the robot and the crane manipulators. The interacting force taking place between them is determined by the formula (1).

Mathematical description of the robot manipulators is carried out on the basis of Denavite-Hartenberg transformation. Vector $\mathrm{x}_r^{(k)}$ is connected with the manipulator joint coordinate by the equation

$$\mathrm{x}_r^{(k)} = T_r\left(\mathrm{q}_r\right) \cdot \mathrm{dx}_r^{(k)},$$

where $T_r\left(\mathrm{q}_r\right)$ is the transition matrix from the absolute system of coordinates to the gripper system of coordinates; q_r is the manipulator joint coordinates; $\mathrm{dx}_r^{(k)}$ are the displacement of the k–th suction cup in the gripper coordinate system.

The dynamics of each manipulator is described by the Lagrange-Euler equation

$$\mathrm{M} = D(\mathrm{q})\cdot\ddot{\mathrm{q}} + \mathrm{h}(\mathrm{q},\dot{\mathrm{q}}) + \mathrm{c}(\mathrm{q}) + \sum_{k=1}^{l}\mathrm{M}_b^{(k)}, \quad (2)$$

where M is the vector of joint forces created by the power drives in the manipulators joints; $D(\mathrm{q})$ is the symmetrical matrix of dynamics with dimensionality of $n\times n$; $\mathrm{h}(\mathrm{q},\dot{\mathrm{q}})$ is the vector ($n\times 1$) of Coriolis and centrifugal forces; $\mathrm{M}_b^{(k)}$ is the vector ($n\times 1$) of external forces; n is the number of joint coordinates

Vector $\mathrm{M}_b^{(k)}$ is stipulated by the influence of communication forces N_k and is connected with them by the ratio

$$\mathrm{M}_b^{(k)} = J_n^{\mathrm{T}}(\mathrm{q},\mathrm{dx}^{(k)})\cdot\mathrm{N}^{(k)},$$
$$\left(J_m(\mathrm{q},\mathrm{dx})\right)_{j,i} = \left(U_{i,m}(\mathrm{q})\cdot\mathrm{dx}\right)_j,$$
$$j=\overline{1,3},\ i=\overline{1,m},$$

where $U_{i,m}(\mathrm{q})$ is the partial derivative of the transition matrix from the base coordinate system to m coordinate system with respect to the i-th joint coordinate.

Construction of the tower crane model is performed with account of elastic deformations in the crane design that arise under the influence of wind and dynamic loads. The model is constructed for movements at low speeds when the amplitude of the wire rope vibrations doesn't achieve great values. In this case wave processes in the rope can be neglected. The adopted limitations for the vibration amplitude are usually carried out on performing the final phase of the panel mounting.

On the basis of the analysis of the crane possible motions with the attached wall panel we have developed an equivalent mechanical diagram of the manipulator. According to the mechanical diagram vector $\mathrm{x}_c^{(k)}$ is connected with joint coordinates of the crane with the equation

$$\mathrm{x}_c^{(k)} = T_c(\mathrm{q}_c)\cdot\mathrm{dx}_c^{(k)},$$

were $T_c(\mathrm{q}_c)$ is the matrix of transition from the system of coordinates to the panel system of coordinates; q_c are joint coordinates of the crane; $\mathrm{dx}_c^{(k)}$ is the displacement of the attachment of the k-th suction cup which is measured in the panel system of coordinates.

The account of elastic forces in the axes of motion is convenient to carry out by the way of introducing additional elastic elements (springs) the rigidity of which is equivalent to the rigidity of the elastic body in direction of the axis of motion movement. Taking into account that the time constant of the drives of the crane axes of motion is by an order less than the links' period of vibration and the drives don't have static mistake then the crane driving force is equal to the sum elastic and dissipative forces arising because of the error in current and stable values of joint coordinates

$$M_c^{(i)} = \left(g_c^{(i)} - q_c^{(i)}\right)\cdot\alpha_i + \left(\dot{g}_c^{(i)} - \dot{q}_c^{(i)}\right)\cdot\beta_i,$$
$$i=\overline{1,n}, \quad (3)$$

where $g_c^{(i)}$, $\dot{g}_c^{(i)}$ are non-deformed positions and velocity of the i-th joint coordinate; α_i, β_i are the coefficients of rigidity and dissipation of the fictitiously introduced spring which coincides in direction with the i-th joint coordinate and the non-deformed state of the controlled coordinates is determined by the angle and rotational speed of the stable position of the additive axes of motion imitating elastic connections are taken as equal to zero.

During the process of mounting the crane may experience substantial influence of the wind load therefore we introduce into the equation (2) a summand taking account of that influence. The concentrated force equivalent to the wind load acting the i-th link will be written in the form

$$\mathrm{F}_w^{(i)} = \left(\vartheta_x^{(i)}(\mathrm{q})P_x \quad \vartheta_y^{(i)}(\mathrm{q})P_y \quad \vartheta_z^{(i)}(\mathrm{q})P_z\right)^{\mathrm{T}},$$
$$i=\overline{1,n}, \quad (4)$$

where $\vartheta_x^{(i)}(\mathrm{q})$, $\vartheta_y^{(i)}(\mathrm{q})$, $\vartheta_z^{(i)}(\mathrm{q})$ are the functions of the unit wind load of the k-th link in the direction of the axes of the base coordinate system; P_x, P_y, P_z is the distribution of the wind flow along the axes of the absolute coordinate system. The obtained force is converted from the Cartesian coordinates to the joint ones

$$\mathrm{M}_w^{(i)} = J_i^{\mathrm{T}}\left(\mathrm{q},\mathrm{r}_w^{(i)}(\mathrm{q})\right)\cdot\mathrm{F}_w^{(i)}, \quad (5)$$

$\mathrm{r}_w^{(i)}(\mathrm{q})$ is the displacement vector (3×1) for the concentrated force point $\mathrm{F}_w^{(i)}$. On the basis of the equations (2-5) we can plot a block diagram of the mounting system model that is presented on the fig. 2 where G is the function determining dynamics of the mechanical part of the manipulator.

The mounting system control provides 2 modes – interactive and automatic. Interactive control is used

at the stage of grasping a panel by the positioning robot when its position is arbitrary and it is difficult to perform joining operations. In this mode an operator with the help of 2 special-purpose handles carries out control of the robot manipulators moving the gripper device so as to join it with the panel. In the automatic mode the process of a panel orientation takes place. It is based on the DMS information about the space position of the mounted object. The basis of the automatic mode consists of the algorithms for the panel position corrections during its installation. The process of the panel erection is carried out with provision for wind loads. The pre-assigned accuracy of positioning at substantial wind loads is obtained at the expense of applying adaptive algorithms of positioning and erecting the panels. Application of the adaptive control for the positioning robot has made it possible to restrict substantially forces in gripping devices.

Planning the trajectory of the mounted panel movement is performed in joint coordinates of the crane $\mathbf{g}_c(t)$. Simulation of the erecting operation is carried out on the grounds of the DMS information and the parameters of the system conditions. As a result of simulation the controlling moments of the positioning robot are determined. A specific feature of the system control is the availability of surplus communication; as a consequence there is a multiplicity of solutions satisfying the movement along the pre-set trajectory. To ensure unambiguity the solution the joint moments are determined on the basis of applying standard control actions in the model. Simulation is performed in real time on the grounds of the measured wind load. The force in the places of vacuum grippers attachments serves as a control quantity. For the purpose of control we suggest to use a continuous proportionally differentiating controller ensuring necessary dynamic and precision characteristics described by the equation of the kind

$$\mathbf{N}^{(k)} = (\delta_m + \gamma_m)(T_c(\mathbf{g}_c) - T_c(\mathbf{g}_m)) \cdot \mathbf{dx}_c^{(k)}, \; k = \overline{1,l}, \tag{6}$$

where δ_m, γ_m are the coefficients of the proportional and differentiating component of control; $\mathbf{g}_m$ are the joint variables of the crane model.The desired distribution of load between the suction cups of the gripper can be obtained by the way of choosing the regulator's coefficients. In order to limit forces in suction cups the system of equations (6) is supplemented with inequalities $\mathrm{N}^{(k)} \le \mathrm{N}_{\lim}^{(k)}$.

The trajectory of the positioning robot is determined in terms of the non-linear equation

$$T_c(\mathrm{g}_m) \cdot \mathrm{dx}_c^{(k)} = T_r(\mathrm{g}_r) \cdot \mathrm{dx}_r^{(k)}. \tag{7}$$

Feedback with real object is implemented by introducing the model parameters correction loop. Measurements of the crane joint coordinates are carried out in discrete moments of time at interval of Δt. Introducing into the system of dynamic equations additional summands performs the model parameters correction

$$\ddot{\mathrm{g}}_m = D_m(\mathrm{g}_m) \cdot \begin{pmatrix} \mathrm{M}_m - \mathrm{h}_m(\mathrm{g}_m, \dot{\mathrm{g}}_m) - \\ - \mathrm{c}_m(\mathrm{g}_m) - \sum_{k=1}^{l} \mathrm{M}_b^{(k)} \end{pmatrix},$$

$$\dot{\mathrm{g}}_m = \int_0^t (\ddot{\mathrm{g}}_m + \Delta\ddot{\mathrm{g}}_m) d\tau,$$

$$\mathrm{g}_m = \int_0^t (\dot{\mathrm{g}}_m + \Delta\dot{\mathrm{g}}_m) d\tau, \tag{8}$$

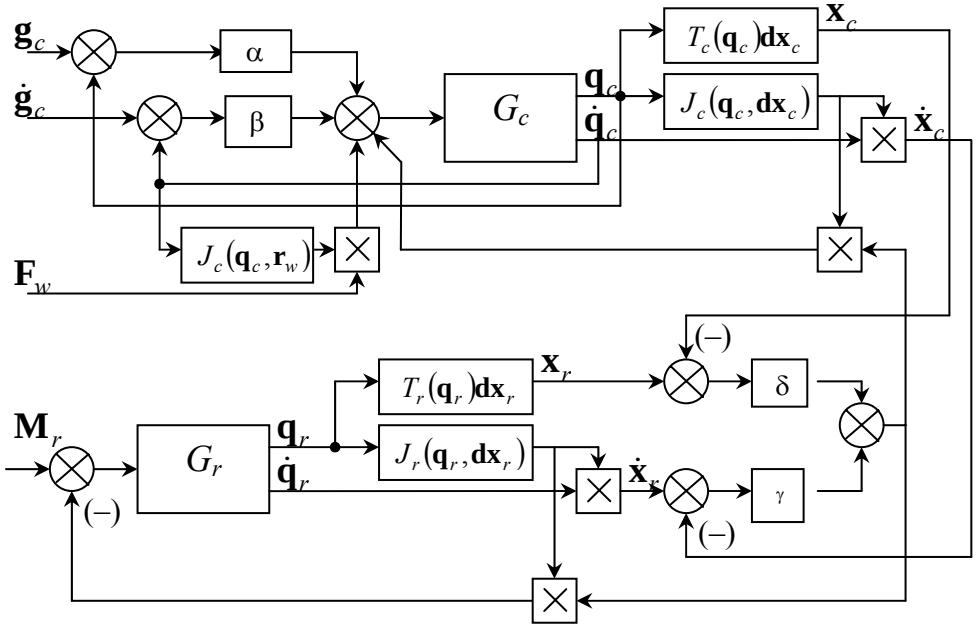


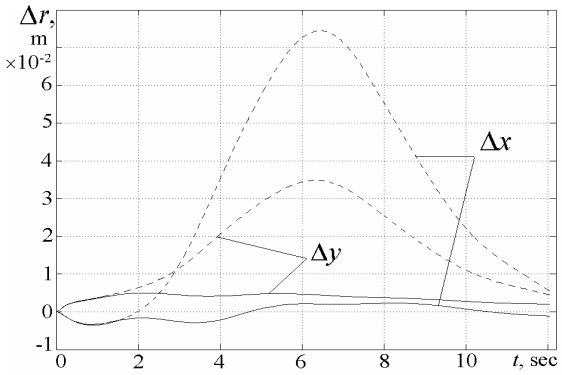
Fig. 2.

Additional summands are determined by the difference of calculated and measured values of the crane kinematic parameters

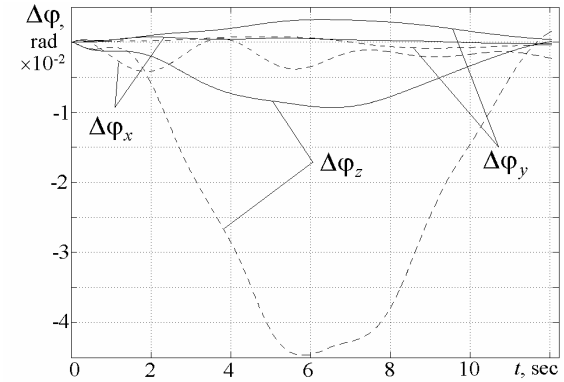
$$\Delta \dot{g}_m = \left(g_m - q_c\right) \cdot \kappa_q ,$$
$$\Delta \ddot{g}_m = \left(\dot{g}_m - q_c\right) \cdot \kappa_{\dot{q}} , \qquad (9)$$

where $q_c[I \cdot \Delta t]$, $\dot{q}_c[I \cdot \Delta t]$ are the position and the speed of the crane joint coordinates which are measured by an observer; $\kappa_q, \kappa_{\dot{q}}$ are the observer convergency coefficients; I is the number of the current measurement.Calculation of the joint forces moments necessary to overcome the robot inertia while going along the trajectory $g_r(t)$ is performed in terms of the calculation method of controlling moments [1].

Applying the stated procedure of the positioning robot control the system operation simulation has been carried out. In fig. 3 one can see the plots of position



– without robot;



– with robot.

Fig. 3.

change and panel orientation during the process of its erection by the positioning robot at wind load. To compare it represents the passage of the erection trajectory by the crane without incorporation of the positioning robot. The investigations have shown that the imposition of constraints of the positioning robot allowed to increase substantially erection speed and the application of adaptive control has provided the system stability to changing wind load.

5. CONCLUSION

The matter for the paper has been prepared in terms of the author's investigations being carried on in the field of robotization of erection works. The presented principles of constructing robotic mounting system are supposed to apply when developing projects for robotization of erection work in the large-panel house-building. The investigations have shown that introduction of the positioning robot into the mounting system substantially increased speed and reliability.

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CONCRETE WALL FABRICATION BY CONTOUR CRAFTING

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Abstract: The feasibility of CC along with its unique capabilities and key performance characteristics (speed, surface quality, material variety, possibility of embedding reinforcement, etc…) have been demonstrated in the construction of relatively large geometrical shapes and structural components using a variety of construction materials. Construction and testing of full-scale concrete wall sections has been the goal of our recent project which this article reports.

Keywords: Contour Crafting; automation; construction; structures; dwellings; fabrication; rapid prototyping.

1. Introduction

Due to advances in sensing technology, numerical machine controllers, and automated drive systems, robotic systems have dramatically increased their performance, capability, and accuracy in recent years. Today robotic systems routinely replace many complicated, tedious, and dangerous human production activities in a variety of manufacturing applications.

During the last 18 years, construction automation and robotics have been implemented at various extents to address problems facing the construction industry such as productivity, quality, safety, high costs and skilled labor shortages in the United State and Japan [1]. The Japanese construction industry, in particular, is very active in automated construction research, seeking a solution to the skilled labor shortage. Many large Japanese construction companies have their own research centers with sophisticated equipment and large staffs researching new construction technologies. Kajima Corporation, for example, spends more than $900M / year on construction research; a significant portion is invested in construction automation [2].

Approximately 89 single task construction robots have been prototyped and deployed in construction sites in Japan [3]. These single task robots replace simple human tasks thereby reducing labor costs and construction time. Automated construction systems such as AMURA, SMART and FACES are capable of fabricating high raised structures. These systems typically use precision fabricated components such as pillars, beams, ceilings, floor slabs and others [4].

However, the usage of single task robots is limited to small construction sectors mainly because the robots cannot detect and fix problems in real time during operation. Also, fully automated construction systems do not allow much flexibility in the design of structures. The cross section of a structural member, for example, cannot be readily changed. A system capable of generating a variable cross section structure would be rather expensive. Furthermore, current automated systems require many prefabricated parts. This translates into extra costs for inventory, transportation, and additional machinery.

Using conventional automation technology, implementing a fully developed automated system that will address the problems facing the construction industry will be expensive. The following barriers hinder the efficient implementation of automation technology in construction [5]:

- Availability of feasible fabrication technologies for large scale products
- Conventional design approaches not suitable for automation
- Small production quantities compared to other industries
- Limitation of material choices
- High equipment costs and maintenance fees
- Management issues

Previous attempts at developing automated construction systems have not adequately addressed these barriers. Current available automation technologies and engineering know-how may not be sufficient to overcome these barriers cost effectively. The construction industry could seek alternate approaches to existing fabrication and assembly processes. The new approach should consider adaptability to automated construction technologies and processes.

In recent years rapid prototyping (RP) processes have been implemented in a variety of applications

and disciplines such as architecture, automobile design, aerospace and medical industries. RP processes are capable of fabricating complex structures, as shown in Fig. 1. However, RP systems today are not suitable for fabrication of larger scale parts. A special RP technology developed at the University of Southern California (USC) is Contour Crafting, which was introduced at the 19th International Symposium on Automation and Robotics in Construction (ISARC) in 2002. CC technology adapts RP capabilities and extends them to the field of large scale construction. As in other RP methods, in Contour Crafting (CC) material is added layer by layer according to a computer control sequence.

Figure 1. A complex geometry (Hagia Sophia in Istanbul) fabricated by a RP process [Source: MIT 3DP Laboratory]

CC is suitable for rapid fabrication of large-scale complex shaped objects with smooth surface finish. The CC extrusion and filling process is shown in Figure 2.

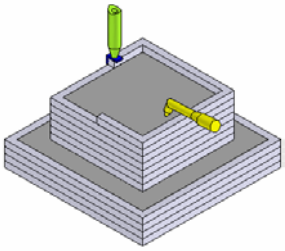

Figure 2. Extrusion and Filling Process

The extrusion process forms the smooth object surface by constraining the extruded flow in the vertical and horizontal directions by the use of trowels. A schematic view of extrusion using a single nozzle is shown on the left side of Figure 3. The orientation of the side-trowel is dynamically changed for better surface fit for each decomposed layer. The side-trowel allows thicker material deposition while maintaining high surface finish. Thicker material deposition cuts down fabrication time, which is essential for building large-scale parts by using the additive process. Maximum deposition layer thickness is limited by the trowel height.

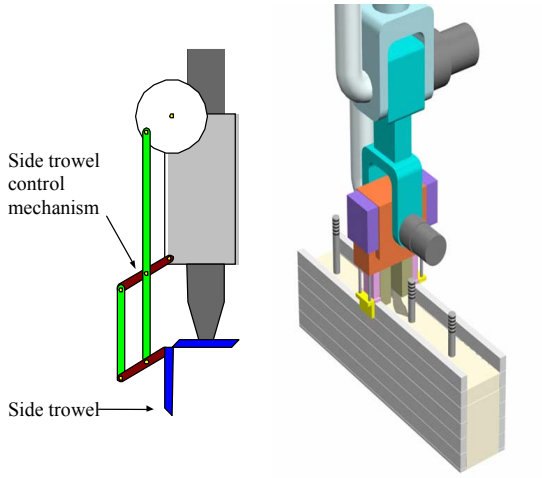

Figure 3. CC single nozzle (left) and multiple nozzle assemblies.

On the right side of Figure 3 a compound nozzle assembly is shown by which concurrent extrusion of two wall sides and filling of the previously built layer may be performed. As the extrusion nozzle moves according to the predefined material deposition path of each layer, the rims (smooth outer and top surface of outside edges) are first created. The troweled outer surface of each layer determines the surface finish quality of the object. The smooth top surface of each layer is also important for building a strong bond with the next layer above. Once the boundaries of each layer are created, the filling process begins and material is poured or injected to fill the internal volume. For viewing several animations of the CC process please refer to www.contourcrafting.org.

3. Current state of research and development

Contour Crafting has been the focus of intensive research at the USC rapid prototyping laboratory. The laboratory has been improving CC's superior surface forming capability, speed, part size and nozzle designs [6-9]. Various materials have been tested and evaluated to date. Rapid advances in this research will be a critical if CC is to be considered as a viable option for construction automation.

3.1 Hardware system design

A special simplified CC nozzle system and a three axis motion control mechanism have been developed for demonstration of full scale wall construction. The new CC system, shown in Figure 4, consists of an extrusion system that conveys a mortar mixture from the material reservoir and deposits it in controllable amounts to form a desired shape. A piston is attached to and driven by the lead screw which turns at constant rotational speed upon extruding the mixture. As the mortar exits the

extrusion nozzle, the machine moves the nozzle assembly in the X-direction at pre-specified speed. extruded form becomes an integral part of the wall.

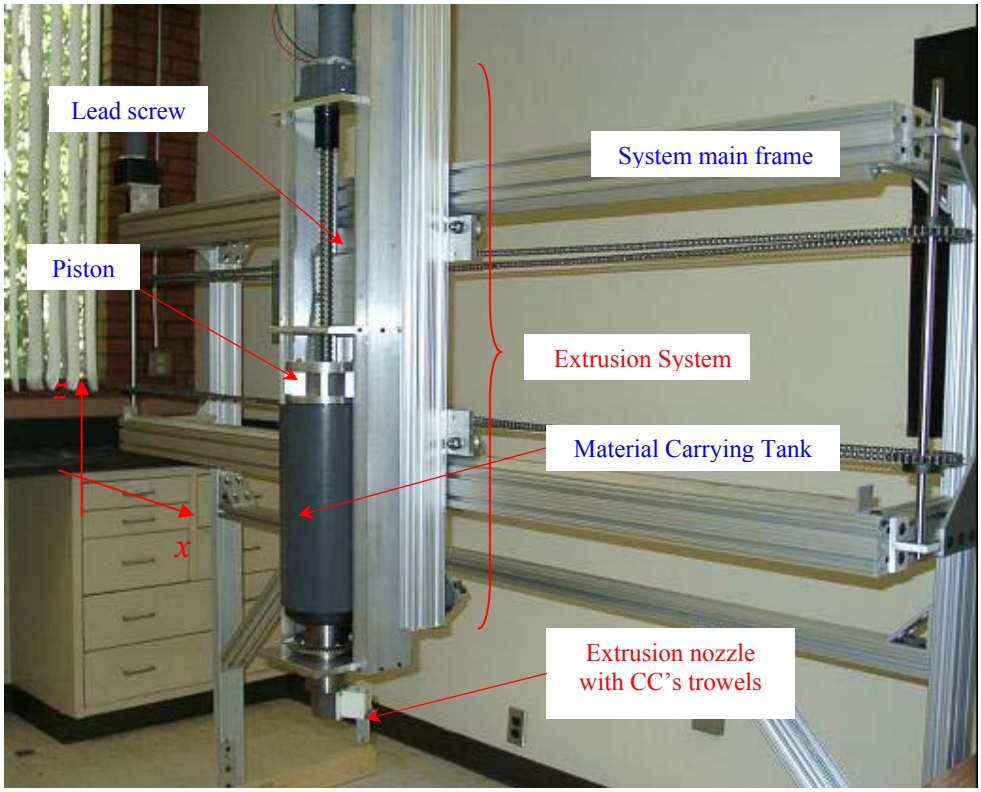

Figure 4. A picture of a new CC machine for fabricating a concrete wall

Once the extrusion system finishes its single layer cycle, the entire extrusion system moves vertically an incremental distance equal to the height of the next layer. The cycle is repeated until the final shape of the boundary is established. The machine structure supports and precisely guides the entire extrusion system during fabrication. The machine frame has two V-shape profiles that are used as a rail to guide the extrusion system. The current frame permits extrusion only in the X and Z directions, therefore is limited in the types of 3-D objects that can be created.

3.2 Target geometry

To reproduce a full scale concrete wall segment, the geometric specifications of a typical concrete wall used in housing construction was pre-programmed. Figure 5 details the wall specifications and dimensions. The concrete form is first fabricated by extruding the material in incremental vertical layers of 19 mm (0.75") in width and 13 mm (0.5") in height. The final concrete form is a hollow wall structure with a curved radius at each end. Following the boundary extrusion, any type of concrete can be poured in as filler structural material either manually or automatically with the CC machine. Filling the inside space with concrete may be also done in a layer-by-layer fashion. After the concrete sets, the The extruded boundary establishes both the internal and external surface finish which plays a key role in the appearance of the finished product.

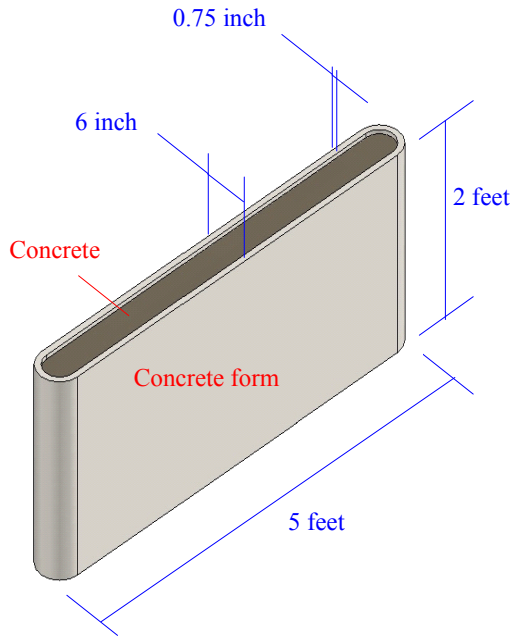

Figure 5. A schematic view of target concrete wall

3.3 CC Nozzle Assembly

To fabricate the target geometry a new CC nozzle system was designed and integrated with a new CC machine. Unlike previous designs, the new CC nozzle is equipped with dual trowels to control both the internal and external surface finish of the extruded rims. Figure 6 shows the new CC nozzle assembly. The nozzle assembly is offset 70mm (2.75") from the flow center of the extrusion system.

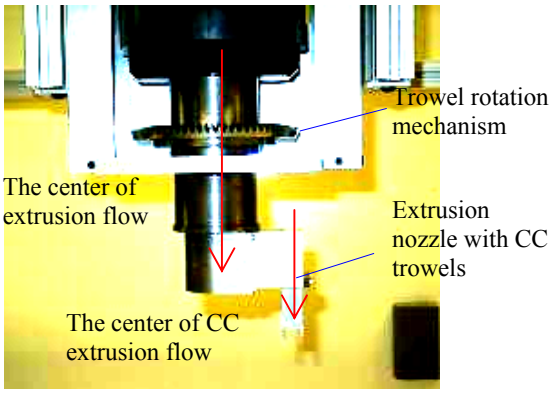

Figure 6. A closer view of CC nozzle with trowels

To fabricate the rounded ends, extrusion in the X-direction is stopped and the assembly is rotated 180 degrees. With this configuration the Y axis is not used, hence reducing the machine complexity at the cost of being limited to fabrication of straight wall sections.

4. Fabrication of a Concrete Wall

The success in fabricating a part using the CC process mostly depends on the extruded material characteristic. Any paste-like material that can be extruded using conventional tooling can also be used in Contour Crafting..

4.1 Mortar Mixture and its Compressive Strength

Extruding a dense mortar mixture through a small nozzle orifice is quite difficult. The optimum mixture ratio of cement, sand, and water necessary to fabricate a concrete form depends on the application. Through several trial and error experiments, a mixture characteristic found to be suitable for the new CC machine is as follows;

- Type II hydraulic Plastic Portland cement: 9.5 lb
- Sand: 10.5 lb
- Plasticizer: 0.8 lb
- Water: 4.8 lb

To verify its early compressive strength, three cylindrical test specimens, 5 cm X 10 cm (2" X 4") were made and cured for 7 days in room temperature. Tests were conducted at USC's Civil Engineering structural testing laboratory with the results shown in Table 1.

Table 1. Results of testing compressive strength

Cylinders	Compressive strength (PSI)
Specimen 1	2,786
Specimen 2	2,830
Specimen 3	2,606
Mean	2,741

The results indicated that the compressive strength of thee test specimens were both consistent and adequate for their use as a permanent structural component of the finished concrete wall. Our research team in collaboration with industry is aiming at the use of mixes that can cure to near maximum strength in a few hours.

4.2 Fabrication

The mortar mixture was prepared using power drill driven mixing paddles and was loaded into the material carrying tank, shown in Figure 4. The velocity of the extrusion system in the horizontal direction was set to 20 mm/sec with stabilized continuous extrusion flow from the CC nozzle assembly. Initial extrusion flow is discarded until the flow is stabilized and the system starts its fabrication. Once an entire batch of the mortar mixture loaded inside the material carrying tank is used up, the CC system pauses until another batch of mortar is loaded and the extrusion continues to form the remaining concrete form. A batch of mortar is consumed in approximately 10 minutes and yields a concrete form approximately 64 mm (2.5") high. To complete the target geometry shown in Figure5, nine batches were needed. The final concrete form fabricated by the CC system exceeded a height of 60 cm (2 feet) and is shown in Figure 7.

4.3 Lateral Pressure on Concrete Form

The function of the concrete form is to contain freshly poured concrete in a contained mold until the placed concrete sets. Lateral pressure against the concrete form is a function of the height and mass of the poured concrete; the pressure is not affected by the wall thickness. The following is a standard formula widely used as a design guide for vertical formwork based on ACI standard 347:

$$P=W*H$$

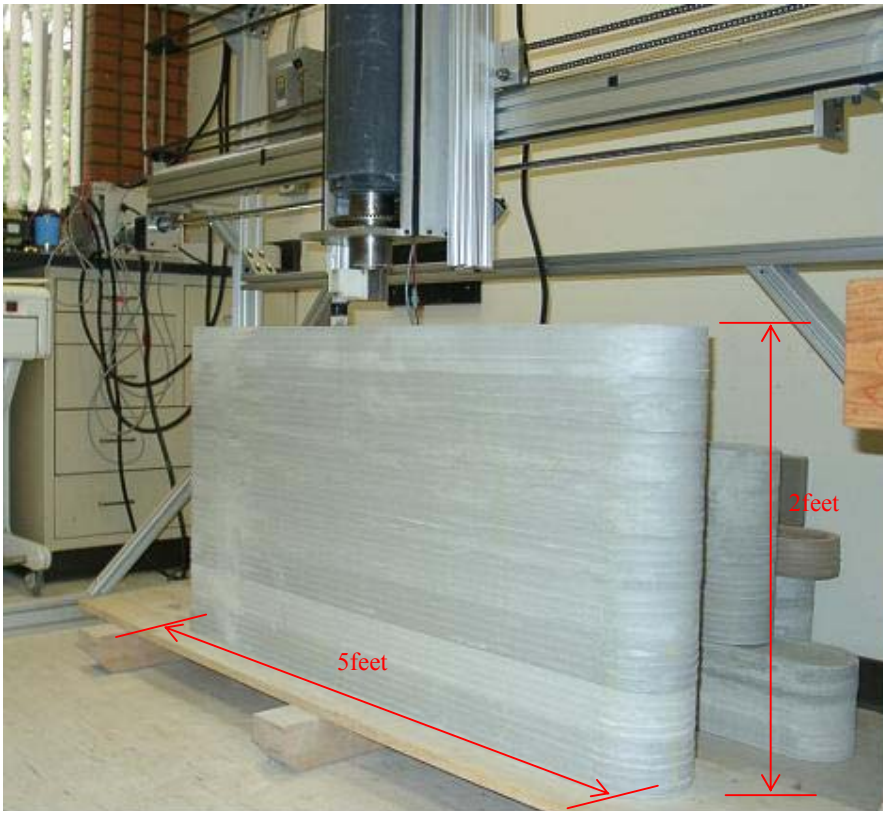

Figure 7. A concrete form of desired span and height fabricated by the CC machine

Where: P = Lateral pressure
W = Unit weight of fresh concrete or 150 pcf for normal weight concrete
H= Depth of fresh concrete

Table 2. Concrete pressure for wall form

Pour rate (ft/hr)	Pressures of Vibrated Concrete (psf)	
	50°F	70°F
1	330	280
2	510	410
3	690	540
4	870	660
5	1,050	790
6	1,230	920
7	1,410	1,050
8	1,470	1,090
9	1,520	1,130
10	1,580	1,170

Some approximated lateral pressures are in Table 2. These are design guides for wall concrete for mwork. The actual pressures may vary. Note that reliable data is difficult to obtain in published references when the pour rate is less than 1 ft / hr.

For CC applications, pour rates less than 13 cm/hour (5"/hour) will allow erection of a 3 meter (10 feet) tall concrete wall without using special high strength form materials. Once concrete inside the form hardens, pressure is no longer generated below the level of fresh concrete. It is not necessary, however, to wait until the concrete hardens completely since even partially cured concrete generates minimal lateral pressure on the form. Figure 8 illustrates the CC concrete pouring process.

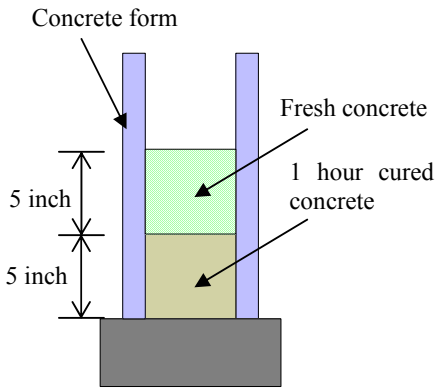

Figure 8. Placing concrete procedures

The bottom cross-hatched section represents concrete which has been cured for one hour. The cured concrete produces minimal lateral pressure on the

form but the exact value was difficult to quantify in our experiments. Data was not available in the available literature; therefore, a simple test was devised to validate the strength capability of the form. Figure 9 shows the test bed.

Figure 9. Pouring concrete in layer by layer

A batch of concrete was poured to a height of 13 cm (5"). The second batch was poured on top of the first batch after one hour without problems. The test procedure, if repeated 24 times, will result in the erection of a 10 feet high "conventional" concrete wall in 24 hours. Ten feet is a standard height for concrete walls in residential housing construction.

5. Results

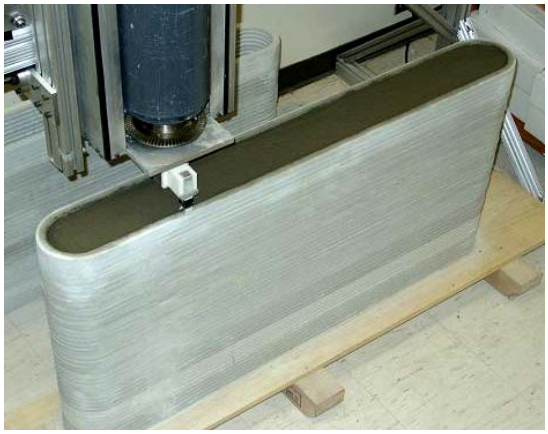

Figure 10. A concrete wall made by CC machine

As described in section 4, concrete was manually poured into the extruded form in 13 cm incremental depths (one hour intervals) to a final height of 60 cm (2ft). Figure 10 shows the finished wall. The compressive strength of this wall will vary depending on the type of concrete chosen. Concrete pouring in this demonstration, however, has been independent of the extrusion forming process. With more experimentation, the filling process can be synchronized with the extrusion process. The coupling of these two processes will depend on many factors including extrusion rate, pour rate, cure time and strength requirements. In the next generation CC system, the mechanical assembly for continuous concrete pouring will be integrated into the CC extrusion nozzle assembly.

5. Conclusion

Contour Crafting is a new approach to solving problems facing the construction industry, particularly at the automation and process level. Currently available automated systems are geared toward conventional construction process and cannot fabricate complex structures nor adapt to sophisticated designs. To be successful, construction automation will require a paradigm shift in process technology. The CC technology fits in this category and has the potential to revolutionize the industry, changing it from the conventional "beam and post" paradigm to a layer by layer approach.

The CC technology is one that is scalable to fabricate larger parts without difficulty. The corresponding increase in cost or fabrication time compares well to other layer based manufacturing processes. Through this research we have shown that the CC technology is capable of using even standard industry materials. CC may hence be regarded as an immediately available technology which can be extended to full-scale housing construction.

Note that due to mechanical speed limitations with the new CC system, actual material deposition speed was not well established in this research. In the next generation CC system design, material deposition speed will be a carefully considered parameter. The goal of the next research phase is to erect a 3 meter (10 feet) concrete wall around a 200 m^2 housing unit within a single day.

ACKNOWLEDGEMENT

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APPLICABLE POSSIBILITY STUDIES ON A HUMANOID ROBOT TO COOPERATIVE WORK ON CONSTRUCTION SITE WITH A HUMAN WORKER

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Abstract: Humanoid robot walks by a pair of legs and works using two hands. About this humanoid robot, authors investigate about the possibility of its application to various works on site.

Investigation is conducted by the following three methods. The first one is an investigation of matching the demand function of the latest work on the construction site with the performance which a humanoid robot holds. The second is an investigation of the way that a worker cooperates with the most advance humanoid robot. In an experiment, they transport a lightweight board from a place to a final work place and attach it together. The name of the humanoid robot used for the experiment is HRP-2, developed by the METI national project. The human worker is a fixtures carpenter. And the third is an analysis of the needs of managers of construction site on the humanoid robot.

The results of the investigation show that a humanoid robot can be applied to the on-site continuation works of 24 hours, works with high stress and degree of fatigue, various impersonal works, works in which sensors are utilized, and the business in a construction site office.

Keywords: Applicable possibility study, Humanoid robot, Cooperative work on site, Cooperative work with a human worker

1. INTRODUCTION

Change of the Japanese population composition for 50 years at the first half of the 21st century deserves attention. The production age or the golden age from 15 to 65 years old decreases by about 33 million people, and 65 or more years old increases by about 9 million people. The reduction in the golden age brings a big change to society and economy. This means that the construction industry will be also influenced greatly. The construction industry must draw up the solution of this subject immediately. In this paper, results of the investigation about the possibility of introduction of humanoid robot to construction site is discussed.

1.1 The present condition and the problem of the construction industry

The labor productivity of the construction industry of Japan has hung low remarkably compared with other industries or the European and American construction industry. Before, time with labor productivity higher than a manufacturing industry also had the construction industry. However, it centered on the manufacturing industry as introduction of automation technology got into stride with the production line of a manufacturing industry, and also the predominancy of the industry was established.

Although the number of workers of construction industry became 6,850,000 people of a peak 1997, they are leveling off or a decrease of fine after it. In the present condition, there is no feeling of a labor shortage like at the time of a bubble term. However, since the younger age group likes the short working hours, and has a tendency to avoid 3K(Dangerous, Dirty, Harsh) so-called work, there is a possibility that near future construction laborers, especially skilled workers may run short. Moreover, a skilled worker's average age are going up steadily and the measure to the laborers of an advanced age is needed to be formed.

From 1961 to today, the industrial accident of the construction industry is continuing the worst accident occurrence number of cases, and occupies 40 to 50%

of all industries. Although the number of the deceased in the construction industry was less than 40% of all industries in 1998, this is also because the amount of construction became less by the economic slump, and the work safety of a construction site is hard to be referred to as having been improved certainly.

1.2 Expectation for the possibility of humanoid robot

Development of the robot for construction has tackled positively from the 1980's that the problem of such the construction industry should be solved. However, most of the conventional construction robot were realized as "an exclusive automatic machine", and it was foundations to take out a scale merit, by managing many finite repetition work. On the other hand, the correspondence to unfixed type work and complicated work and movement of the irregular ground are possible for a humanoid robot. Moreover, since a humanoid robot has affinity with human, it can share the work on condition of man and it is suitable for working in harmony with man. Because of it, it is expected to robotization of construction work as what opens the new possibility.

2. METHOD OF INVESTIGATION

Humanoid robot walks by a pair of legs and works using two hands. Authors investigated and examined that what work is suitable for this humanoid robot working in cooperation with man on a construction site, and that what performance and capability of robot were needed again in that case. Below, the concrete investigation method is described.

2.1 The enforcement items of investigation

Investigation was conducted in the following methods and procedures. First, investigation of matching the function of the work of the construction site with the performance of a humanoid robot was conducted. It referred to the level demanded by the work of a construction site for every robot's performance and capability, and the future subject was clarified. Next, one construction work was made to do experimentally using the humanoid robot which is advancing most in the present condition, and the subject required for utilization was extracted. Furthermore, the needs of construction site were analyzed, the conditions of the work which heightens the introductory effect of humanoid robot were clarified, and the concrete example of application was shown.

2.2 Humanoid robot which was investigated

The humanoid robot made into the object of investigation this time is a robot with which it is referred to as HRP-2 and development is progressing most in Japan now. Research and development in this robot was done in "Humanoid Robotics Project" of the Ministry of Economy, Trade and Industry undertaken from 1998 to 2002. Figure 1 shows the appearance of HRP-2 and an example of its application, and Table 1 shows the main performance specification. HRP-2 can walk along the irregular ground. Moreover, while the man itself who does cooperation work worked, it became possible to manage a robot. For the purpose, a new robot's hardware, advanced 2-pair-of-shoes walk technology, the communication technology of man and a robot, environmental recognition technology, the cooperation control technology of arm and leg, etc. were developed.

3. INVESTIGATION BY FUNCTIONAL ANALISYS METHOD

In this investigation, the performance and capability which are needed for the humanoid robot which does construction work first were developed over several order. Next, the function of the work being done in the usual construction site was similarly developed over several order. Furthermore, this robot's performance and capability, and the function of construction work were made to contrast, and the matrix was created. Based on this matrix, the level demanded in the construction spot was compared with the present level for every a robot's performance and capability, and future research subject and target were clarified.

3.1 Functional deployment of performance of humanoid robot

The result which carried out functional deployment of the performance and the capability needed for a humanoid robot is shown in Table 2. As primary deployment, seven items of "move capability", "work capability", "intention transfer capability", "reliability", "knowledge power", "recognition capability", and "judgment capability" were chosen. Secondary deployment is items of the individual performance or capability included in the item of primary deployment. The 3rd deployment has specified the contents of each item technically further. Usually, the object which specifies a performance and capability when designing a robot is the level of this 3rd deployment. This functional deployment was performed on condition that the following.

[1] It considered as the object of deployment of performance and capability of a robot required to do actual work, such as autonomy, athletic ability, etc.

[2] The performance required to do outdoor work, such as irregular ground movement, was also made into the object of deployment.

[3] It considered as the object of deployment of capability required to do cooperation work, such as intention transfer capability.

3.2 Functional deployment of construction works

The work function currently carried out in the general construction site was developed. As primary deployment, nine items of "a preliminary survey", "temporary work", "digging and the foundation", "underground structure", "ground structure", "waterproofing", "finish construction", "equipment construction", and "exterior and inspection" were taken up. Furthermore, deployment to the 4th order was performed about each function. A part of result developed to the 4th order is shown in Table 3. This functional deployment was performed on condition that the following.

[1] Planning, implementation and inspection of construction work were set as the object of deployment. However, the row of the developed function is not in agreement in order of actual work.

[2] Functional deployment was performed based on so-called 4M. Construction plan, drawings, manuals, etc. are mentioned as Method. As Man, they are supervision persons, administrators, workers, etc. As Machine, they are construction machines, temporary materials, tools, inspection apparatus, etc. Moreover, many building materials are mentioned as Material.

[3] The function about the safety and the environmental problem of work was also considered subordinately.

3.3 The degree analysis of relation of a robot's function and construction work

Based on deployment of construction work and a robot performance, the degree of relation of construction work and a robot performance was examined. In order to examine this degree of relation, the functional contrast matrix described below was created. The vertical axis of the matrix is the developed construction work function. (The 4th deployment of Table 3, 262 items) The horizontal axis is developed about a robot's performance and capability. (Secondary deployment of Table 2, 26 items) Each cell of the matrix evaluates the strength of both degree of relation. Evaluation of the strength of the degree of relation was evaluated in seven stages (0-6) for every cell. Average value and the standard score were calculated about construction work function, and each performance and capability of a robot using this figure. Especially the strong thing of relation with construction work function was the following 13 items in a robot's performance and capability as a result of this analysis. They were an "irregular standpoint line", "course generation", "transportable weight", "hand flexibility", "positioning accuracy", "conversation capability", "communication capability", "fall stability", "on-site data", "material knowledge", "memory", "image recognition", and "various sensing". About these 13 items, the subjects and target of research and development which should be done from now on were clarified by grasping the difference of the required performance level and the achievement level of HRP-2. Table 4 shows the examined result about "Conveyance weight" as an example.

4.APPLICABILITY INVESTIGATION BY WORK EXPERIMENT

The construction work supposing HRP-2 developed this time was work which carries a lightweight wall panel in harmony with man, and is built in a building. The human worker is a fixtures carpenter. Based on the result of a construction experiment, the application possibility to the actual site was investigated about this selected work.

4.1 The contents of work set as the object of investigation

The flow of the work used as the candidate for investigation is as follows. First, the robot detects the dump of wall panels by the image recognition of installed camera, and walks to near it. Then, after detecting again the position which holds a panel by image recognition correctly, the panel is lifted in harmony with a human worker. And a panel is carried in harmony with him, receiving directions by voice and power feeling of a human worker. If a building is approached, the robot will build a panel in the building in response to voice directions of the human worker. Photograph 1 shows signs that the position where the robot holds the panel is detected. Photograph 2 shows the situation of carrying the panel in harmony with man. Moreover, photograph 3 shows signs that a panel is built.

4.2 Evaluation of the application possibility in the supposed work

The contents, and its conditions and required capability of the work being done in the general construction site were investigated about conveyance and assembly work of wall panels. On the other hand, the contents of the work supposed by HRP-2, and the results of the experiment was summarized in Table 5. Furthermore, comparison contrast of both was performed, performance and capability of the robot which runs short of realizing conveyance and assembly work of the wall panel in the actual construction site were summarized. Table 6 shows future research subjects and target.

5. INVESTIGATION OF THE APPLICATION POSSIBILITY SEEN FROM THE POSITION OF CONSTRUCTION SITE

Before introducing a humanoid robot into the construction site, what should be kept in its needs and mind by the side of the site was examined.

And based on it, the conditions on which humanoid robot demonstrates an introductory effect on the site were probed, and the concrete works and business in the site suitable for the condition were selected as an example of application.

5.1 Change of the construction site expected by the introduction of humanoid robot

Concerning to the subject of the construction industry stated in Chapter 1, the shift from the production system of the conventional human subject to the system of the machine subject is required. In the site where it was mechanized and the robots were introduced, the following change is expectable.
[1] A suitable work assignment of man and robot is performed, the work method and procedure are simplified and settlement of component is also simplified so that it may be easy to robotize work.
[2] The unit of work management will turn into an hour unit from the present day unit. Materials are just carried in to an in time and real time production control system also comes to be performed.
[3] The amount of carrying in and the amount of assembly work of materials increase. Therefore, the role of the site plant prepared in site becomes important. By this site plant, the construction site can be worked like a manufacture factory and operation also becomes possible for 24 hours.
[4] The measure for calamity prevention on a construction site accelerates. By a robot's introduction, a possibility that perfect safety of the site which was years of wish of the construction industry will be realized increases.
[5] If a humanoid robot is introduced, curtailment of the worker station and smoking place, toilets, dining-rooms etc. which were required only for human workers is attained, and can reduce construction expense.

5.2 Works of high application possibility of humanoid robot

In consideration of the feature of a humanoid robot, and technical implementability, work and business equipped with the following conditions were selected as a candidate for application from construction work functions. According to progress of future technical development, first, as the first step, the theme of [1], [2], and [3] should be tackled, and the subject of [4], [5], and [6] which is the ultimate purpose should be challenged in the next step.
[1] Work and business which do not require advanced functions, such as an irregular standpoint line and complicated handling
(ex.) Entrance and leaving management of workers, the surveillance in the site, survey, operation of the elevator for construction, etc.
[2] Work and business which can fully employ efficiently various kinds of sensor ability which the robot equipped
(ex.) Check of the equipment for work safety, or the equipment for security, construction inspection, quality check, etc.
[3] Work and business which can employ efficiently the capability that a lot of information is far held compared with a human worker, and the information on external can be taken in on real time
(ex.) An on-site administrator and a design supervision person are provided with information, such as a plan document and the construction point, on real time.
[4] Work and business which man does not want to do personally even if some are inferior to a human worker in respect of capability.
(ex.) Cleaning of the health facilities in the site, cleaning of floor or glass
[5] Work and business which must do prolonged simple repetition work, without feeling stress and fatigue
(ex.) Night work of the public works in a city., conveyance and repetition work of an assembly, the crime prevention patrol around on-site
[6] Work and business as which continuation work is required like operation for 24 hours
(ex.) Concrete placing of silo construction etc., rush work at the time of construction delay

6. FURTHER RESEARCH SUBJECTS

In order to adopt a humanoid robot as the work or business of an actual construction site, we have to solve many technical subjects. We have to tackle research and development of the hand's dexterity, work speed, and the stable walk on an irregular ground, cooperation control with man or a robot, improvement in reliability or durability, etc. Furthermore, the examination of the design proposal of a construction production system on condition of introduction of humanoid robot, and the improvement in a robot's cost performance will also become future big research subjects.

Acknowledgments

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Figure 1. HRP-2 and an Example of its Application

Table 1. Main Performance Specification of the HRP-2

Dimensions	Height	1,539mm
	Width	621mm
	Depth	355mm
Weight (including Battery)		58kg
Degree of Freedom		30D.O.F
	Neck	2D.O.F
	Waist	2D.O.F
	Arms	6×2D.O.F
	Hands	1×2D.O.F
	Legs	6×2D.O.F
Speed		Max.2.0km/h
Hand Grip Force		2kg/each arm
Conveyance Weight		6kg/both arm

Table 2. Functional Deployment of the Robot's Performance and Capability

Primary Deployment	Secondary Deployment
Move Capability	Irregular ground movement
	Move speed
	Move course generation
	Conversion of direction
Work Capability	Conveyance weight
	Speed of operation
	Movable range
	Flexibility of a hand
	Positioning accuracy
	Continuation operation time
	Working hours
Intention transfer capability	Conversation capability
	Communication capability
Reliability	Stability over falling
	Protection nature to falling
	Danger of reckless move
	Frequency of failure
Knowledge power	Construction site data
	Knowledge of materials
	Memory capability
	Knowledge of regulations
Recognition capability	Image recognition
	Detection of states
Judgment capability	Circumstantial judgment
	Change of procedure
	Common sense

Table 4. Results of the Analysis about "Conveyance Weight" (as an example)

Primary Deployment: **Work Capability**
Secondary Deployment: **Conveyance Weight**

Required performance level in actual site

Kind of work	Performance Level	Frequency
Mold assembly	5 to 10kg	much
Iron bar assembly	2 to 20kg	very much
Concrete placing	5 to 10kg	very low
Lifting up work	5 to 8kg	very low
Interior finish work	10 to 20kg	very much
Equipment work	5 to 30kg	much

Achieved performance level of HRP-2

Hand grip force	2kg/each arm
Conveyance weight	6kg/both arm

Subject and target of future research and development

STEP1	
Required period	5 years
Target of performace	Conveyance weight 15kg
Realizable works	Interior finishing panels, Equipments
Conditions for realizing	Frexibility of hands, Acquisition of work know-how, Rise and fall of scaffold, etc.

STEP1	
Required period	10 years
Target of performace	Conveyance weight 30kg
Realizable works	Iron bars, Wooden and metal fittings
Conditions for realizing	Improvement in capability of handling, knowledge and movement, etc.

Photograph 1. Detection of the Holding Position

Photograph 2. Situation of Carrying a panel

Photograph 3. Signs of a Panel Building

Table 3. Functional Deployment of the Construction Work

1st Deployment	2nd Deployment	3rd Deployment	4th Deployment
Finish construction	Display of attachment position	Grasp of the attachment position information	Grasp of the position and size of ground material
			Grasp of the position and size of finish material
			Grasp of the position and size of openings
		Display of the attachment position of component	Check of the datum lines
			Display to the floor of the attachment position
			Inspection of the position displayed
	Guidance of the carried-in component	Check and directions of a track	The check of the body number of a track
			Directions of the waiting circle place of a track
	Inspection of the carried-in component	Check of the ID-number of carried-in component	Check of the kind and quantity of component
		Check of the contractor who uses the component	Check of carrying-in schedule of the contractor
			Connection to the receipt contractor
			Delivery of the components to the contractor
	Stock of the carried-in component	Check of the place and stock work execution	Collation of the stock yard to the component
			Stock to the specified yard of the component
	Transport to the conveyance place	Check of the kind and quantity of the stocked component	Check of the kind of stocked component
			Check of the quantity of the stocked component
		Transport of the selected component	Putting on a truck of the components
			Transport of the truck to the conveyance place

Table 5. Results of the Construction Experiment by applying the HRP-2

Work element	Contents of the experiment	Attained performance
Check of panel dump	Direction with human voice	Understanding of the registered conversation sentence
	Search of a panel position with camera	Recognition of 2 or 3m away panels by image processing
Walk on calculated course	Course calculation to panel dump	Calculation of the course to a panel dump
	Walk movement	Walk movement along the calculated course
	Walk of the irregular ground above floor	Walk of the level difference of 40mm, and 5% of inclination ground
Check of grasping position	Direction with human voice	Understanding of the registered conversation sentence
	Search of a panel position with camera	Recognition of panel edge by image processing
	Compensation of the standing position	It walks and rectifies in the position suitable for holding a panel.
Grasp and lift of a panel	Direction with human voice	Understanding of the registered conversation sentence
	Positioning the hand and grasping panel	Holding of a panel by closing the 1 flexibility hand
	Lifting a panel	Lifting of a panel of weight which can be conveyed
Conveyance of a panel	Direction with human voice	Understanding of the registered conversation sentence
	Guiding a panel in arbitrary directions	Power and torque felt by the wrist determine a direction.
Build lump of a panel	Direction with human voice	Understanding of the registered conversation sentence
	Stop of holding a panel	Opening the 1 flexibility hand
	Raising and building a panel	Walking forward pushing a panel

Table 6. Future Research Subjects and Target

Performance	Research subject	Development target
Irregular ground movement	Enlargement of height difference and inclination	10cm of height difference and 10% of inclination
Move course generation	Function to avoid obstacle	Detection and avoidance of opening and obstacle
Conveyance weight	Increase of conveyance weight	Conveyance of 15kg weight by both hands
Flexibility of a hand	Grasping of tools and cylindrical materials	Flexibility of opening/closing and gripping
Conversation capability	Increase the registered conversation sentence	Registration of sentence of lots of common operations
Communication capability	Acquisition of information from evnironment	Data acquisition utilized RFID and data-base
Image recognition	Increase of the candidate for detection	Object recognition of 100-piece order
Detection of states	Contents reading of state display equipment	Reading of bar code or scale of display equipment

A Study on Development of the Automated Vertical Controllable Pilot-type Equipment for PHC Piles

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Abstract: This research is intended to develop a pilot type of automated pile verticality control equipment for PHC piles and motivated by a desire to address problems inherent in as-is verticality control exercise during pile driving. The paper provides understanding of the current verticality control methods and associated problems, design and manufacturing of the automated equipment pilot type, its testing and discussions of the results.

Keywords: PHC pile, vertical control, pile driver, automated equipment, servo system, pilot type

1. Introduction

1.1 Purpose & Background

Installation of Pre-tensioned Spun High Strength Concrete piles (hereinafter "PHC pile installation") widely used in foundation work of architectural/civil structures such as apartment housing or hybrid commercial/residential building complex is broken down to setting the vertical center of a pile, pre-boring and pile driving, and pile cap removal.

If the verticality of pile is not maintained in pre-boring and pile driving, bending moment is applied to the pile and the pile is fractured or its load-bearing capacity is reduced if the bending moment exceeds the fracture limit of the pile material. Therefore, automated pile verticality control equipment that can maintain verticality of PHC piles in real time needs to be developed and this research intends to develop an initial pilot type of the aforementioned automated verticality control rig.

1.2 Scope & Methodology

PHC pile driving method is largely broken down to direct pile driving method and pre-boring & pile driving method, however, direct pile driving method is hardly used these days as it involves environmental nuisances such as noise, vibration or dust notably at construction sites located downtown. Therefore, the scope of this research has been limited to automated verticality measurement and control of pile drivers used in relation to concrete pile installation by pre-boring and pile driving method and the as-is verticality control process and associated issues were studied in a site investigation. In addition, relevant technical development cases were analyzed to identify key element technologies of the automated pile verticality control equipment to be developed and arrive at its conceptual design. A pilot type was developed and tested as a part of this research to provide references for further development of prototype.

2. Pile Verticality Measurement & Control

2.1 As-Is Verticality Control Process & Issues

A site trip was made to OO corporation plant located in Ulsan City, South Gyeongsang Province, where pile drivers and associated parts were manufactured to study characteristics of as-is pile verticality measurement & control rigs. A trip to 4 construction sites was made to identify as-is pre-boring and pile driving process.

Representative pile driver used in pre-boring pile driving method is as shown in Figure 1.

Figure 1. Pile driver used in pre-boring method

As indicated in **Figure 1,** the pile driver is consisted of main body where operator cabin and hydraulic power motor are located, auger and auger driver, pile leader that guides the auger in a track, back-stay cylinder controlling the pile leader movement and angle gauge attached to the side of the pile leader.

The site trip has found that the as-is pre-boring process comprises of following steps:

1. Site crew marks pile driving location with steel reinforcement bars and indicates pile leader location with hand signal;
2. Pile driver operator checks verticality with angle gauge and site engineer or experienced site crew measures pile leader verticality with plumb;
3. Bore a hole in the pile driving location with auger;
4. After the hole is completely bored, draw out screw attached to the auger and move pile to the hole;
5. Put pile in the bored hole;
6. Drive the pile to the required depth by free fall;
7. Once pile driving is completed, move on to the next pile driving location.

Pile verticality is measured 1) by operator preliminarily using angle gauge attached to pile driving system, 2) by assistant crew, measuring pile leader verticality with a water level ruler, 3) by assistant crew or a supervisor, checking verticality against pile leader with naked eyes, or 4) by assistant crew or a supervisor, comparing horizontality/verticality in reference to adjacent buildings with naked eyes.

Domestic standards require pile verticality to be maintained or pile verticality control rig to be used in pile driving, but, fall short of providing for specific criteria or methods for verticality measurement. As specific technical criteria for measuring and determining pile verticality is not available, verticality of pile foundation that is critical as it bears the load of structures tends to be dependent on skills of workers and failure of pile or reduction of load bearing capacity of pile resulting from human errors of site crews may lead to structural instability of buildings.

Figure 2. Verticality Measurement with Angle Gauge

2.2 Needs for Automated Verticality Control Rig & Analysis of Its Feasibility

A 5-minute rating was used in this research to measure productivity. Pile verticality was measured across the entire range of piling work including pile driving location designation, leader verticality measurement, pre-boring, moving pile to location, pile lowering, pile driving and piling area clearing and major measurement targets were one backhoe operator, one pile driver operator and one assistant crew. The pile driving sequence involved 10 piles in total and 1 pile driving cycle took 11 minutes and 20 seconds on average.

As indicated in **Table 1**, productivity was measured in the order of backhoe operator (100%), pile driver operator (77%) and assistant crew (15%), which indicates that the assistant crew was responsible only for measuring verticality when marking piling location in the initial phase of the observed piling sequence, remaining idle for the rest of the process and showing relatively low productivity level in turn. It is also to be noted that the accuracy of verticality measurement to be factored in work quality was largely dependent on the skills of a worker without any objective measurement and control methodology in use.

Moreover, the assistant crew had to wait for more than 10 minutes at idle to perform verticality measurement that took only 5 seconds.

Table 1. Productivity Assessment by 5-Minute Rating

Classification	No. of Rating (A)	No. of Works (B)	Productivity (B/A *100)
Backhoe Operator	52	52	100
Pile Driver Operator	52	40	77
Assistant Crew	52	8	15
Total	156	100	64

When analyzing the role of the assistant crew in reference to the flow of the entire work process, following observations were made in regard to the time spent by him and his interface to other work sequences.

First of all, the sequence for which he was responsible required far less time than the other sequences, which indicates that the job of assistant crew is not critical to piling work and his productivity is bound to be low as he is not actively involved in most of the work process.

In terms of his interface to pre-boring sequence, most of his job did not have any significant influence on the main part of the piling exercise and his step is rather likely to lower the overall productivity of piling sequence.

In short, it is concluded that verticality must be secured to ensure accuracy of work and expedite the overall work sequence of piling and automation is required to reduce inefficient work elements involved.

2.3 Current Technical Trends in Korea

2.3.1 Technology Development in Korea

Technologies available at home in regard to pile behavior and pile driver control can be summarized as in **Table 2**.

Table 2. Domestic Technologies Regarding Pile Driver & Pile Driving

Regarding Pile Driver Verticality	Regarding Pile Behavior	Regarding Pile Driver
1. Removable axle verticality measurement & control device 2. Boring machine verticality guiding device 3. Auger machine verticality control device	- Pile displacement measurement during driving with high speed line scan camera	- Pile driver over-turning prevention device

Firstly, removable axle verticality measurement and control equipment is a device that can be attached to machines to measure and control verticality of axle quickly and accurately. Secondly, boring machine verticality guiding equipment is used in small pile drivers to maintain verticality of its head guide by supporting the lower body of the head guide with removable device to prevent head guide from shaking and fix it in location. Thirdly, auger machine verticality control equipment was developed to be mounted on a crane modified from backhoe and maintain leader to be vertical in reference to the ground during boring to improve work efficiency. In addition, pile displacement measurement during driving and pile driver over-turning prevention equipment may be considered in the context of this research.

2.3.2 Technology Development Abroad

As for applicable technologies available abroad, firstly, automatic vertical controlling device for pile driver that was developed to prevent momentary derailment of control system at the start of work and secure stability of vehicles by reducing acceleration of cylinder rod when pushed ahead by the leader. Secondly, a vibratory equipment designed to prevent vibration of vibratory equipment used in crushing, excavation and stone destruction by supporting both vibration prevention device and bracket has been developed in Japan. The support device is intended to prevent failure of the equipment resulting from vertical vibration and reduction of work efficiency of the operator.

As studied so far, the technologies currently available either use ancillary devices attached to the pile driver to fix pile driver leader position or control pile driver position with analogue mechanism before boring or pile driving starts, failing to monitor and control pile displacement consistently while piling is in progress.

2.4 Criteria for Automation

Automation priority was analyzed in a matrix (**Figure 3**) of work tasks and consideration items to identify elements to be considered in development of automated verticality measurement & control technology. Safety hazard, limitation of manual measurement/control and cost impact were selected as items for consideration in determination of automation-qualified tasks and priority ratings of piling tasks were analyzed in 4 site visits and following discussions.

In the matrix analysis of potential candidates for automation, automation of body horizontal measurement was rated lower in terms of safety hazard and cost impact while automation of body horizontal control was also rated lower in reference to the same items as quoted in the above.

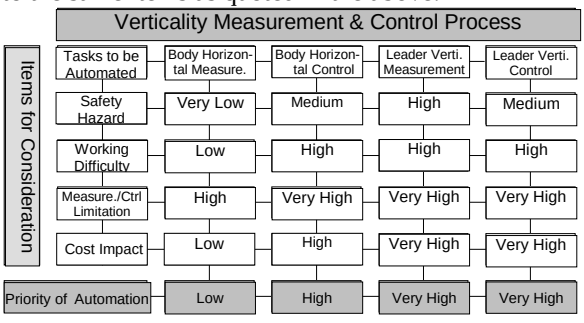

Figure 3. Matrix Analysis of Automation Priorities

2.5 Design Factors

Technological elements considered to develop automated equipment capable of performing two target tasks described in 2.4 are as follows:

1) Select a digital position sensor that can determine verticality of pile driver leader in reference to gravity direction; 2) Develop a digital hydraulic valve that can control hydraulic cylinder of as-is pile driver automatically; 3) Develop a system that can control the digital hydraulic valve with interface to the selected position sensor; 4) Configure the system to be actively responsive to displacement triggered by increase in leader elevation; 5) Develop an automated system that can work independently without the help of assistant crew and measure/Contr ol verticality in a clear and objective manner without relying on subjective judgment of the operator.

3. Pilot Type Development

3.1 System Configuration & Conceptual Design

Four alternatives applicable to development of automated pilot type equipment intended to resolve the issues in the as-is verticality control arrangement described in the above and provide four key functions selected to be automated were presented and optimum concept was selected through various analysis to provide a basis for conceptual design. (See **Figure 4**)

3.1.1 Comparison among Alternatives & Key Functions of Pilot Type

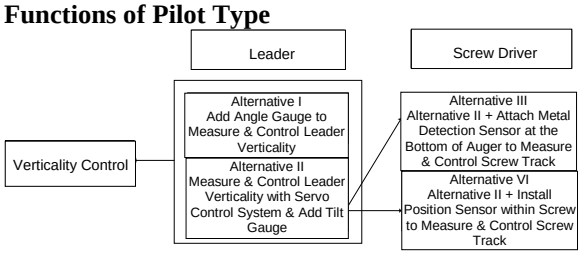

Figure 4. Description of Alternatives

Alternative 1 proposes that additional angle gauge be attached and hydraulic pump controller installed onboard respond to leader behavior measured by two angle gauges. Alternative 2 assumes that servo system is installed in back-stay cylinder to measure linear behavior of back-stay cylinder in real time with interface to hydraulic pump controller to control leader verticality automatically. In Alternative 2, displacement of bending behavior measured by tilt gauge is reflected on back-stay cylinder control to reduce error in vertical control. Alternative 3 is based on Alternative 2 plus metal detection sensor mounted on the bottom of auger driver to measure screw track in real time. Alternative 4 employs Alternative 2 plus position sensor attached to the joint between screw drivers to detect boring defect caused by bending moment of screw driver in advance.

3.1.2 Determination of Optimum Alternative

To determine optimum conceptual design, the aforementioned alternatives were assessed in terms of technical feasibility, durability, user convenience and economic viability as a part of this research. Alternative 2 was favored in terms of accuracy and technical feasibility over Alternative 1 that used analogue approach to analyzing bending moment of leader and controlling back-stay cylinder. The former was also assessed to be the most practical as it conceptualized a system measuring and responding to back-stay cylinder displacement. Alternatives 3 and 4 were found to be limited from both economic and technical perspectives given the level of technologies available at the moment. Given the outcome of assessment described in the above, conceptual design was developed based on Alternative 2.

3.1.3 Conceptual Design

The conceptual design requires servo valve and linear transducer to be installed in back-stay cylinder of pile driver to measure/control linear behavior of the back-stay cylinder and each tilt gauge to be attached to the top and the bottom of leader respectively to measure/control leader displacement and deformation by bending behavior automatically.

Interfacing leader displacement by bending moment measured by two tilt gauges to linear transducer measuring back-stay cylinder displacement can reduce the range of verticality control error. **Figure 5** shows interaction between change in leader behavior measured by the tilt gauge and linear transducer in back-stay cylinder.

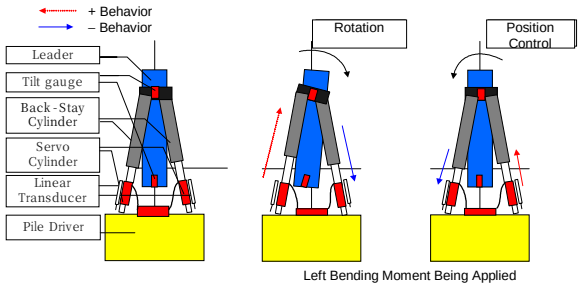

Figure 5. Conceptual Design of Pilot Type Adopting Servo System

3.2 Manufacturing & Assessment of Pilot Type

3.2.1 Detailed Design

The pilot type developed in this research is a 1:20 scale model that adopts a servo system as opposed to hydraulic system found in conventional pile drivers for more precision in control and uses linear transducers attached to both sides of cylinder to enable automated control in response to feedback on cylinder rod position. (See **Figure 6**)

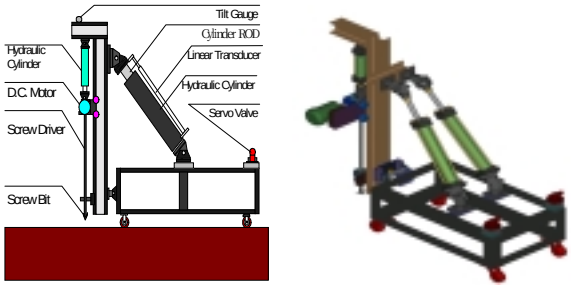

Figure 6. Equipment Configuration & 3D Image

Specifications of the pilot type is as described in **Table 3**.

3.2.2 Test Results & Performance Evaluation

Performance test of the pilot type was conducted three times in the 1st year. The performance test consisted of discrete function test of each configuration element (1st & 2nd tests) and system operation test (3rd test).

Description and result of each test is as follows:

Table 3. Specifications of Pilot Type

Height				1.73 m
Width				0.60 m
Length				1.50 m
Hardware	Cylinder	Cylinder type		Hydraulic servo cylinder
		Cylinder size	Bore	38 mm
			Stroke	400 mm
		Cylinder speed		10 m/sec
		Hydraulic pressure	Min.	20 kg/cm2
			Max.	210 kg/cm2
		Hydraulic volume		30 L/min
	Servo valve	Hydraulic pressure available		210 kg/cm2
		Hydraulic volume available		30 L/min
		Frequency		15 Mhz
	Tilt gauge	Measurement Limit		+/- 5 degree
		Sensor sensitivity		0.1 ms
	Feedback mechanism	Linear transducer	Voltage measurement	+/- 10 V
	Controller	CPU type		Intel CPM8401
Software	Control Program			C

1) The 1st Function Test

The 1st test was designed to determine whether the servo valve would operate as intended on hydraulic pressure from hydraulic pressure supplier.

The system comprises of hydraulic pressure supplier, servo valve, linear transducer and controller. First of all, the hydraulic pressure supplier can supply hydraulic oil from 20kg/cm^2 to 220kg/cm^2 in terms of pressure and at 30L/min in terms of volume. The supplying capacity was set to 70kg/cm^2, 30L/min in the 1st test. The Servo valve opens proportionately at analogue signal from the controller. The signal is from 0 to 40mA and the valve opening control at signal was confirmed. Stroke of the cylinder was from 0-400mm and the linear transducer generated voltage difference from 0-10V. During the test, it was confirmed by measuring change in linear transducer length that the servo valve controlled hydraulic pressure properly to operate the cylinder back and forth as intended at the command from the controller.

2) The 2nd Function Test

The 2nd test was intended to find out whether the servo valve controlled leader position in reference to tilt gauge measurement. In other words, the test objective was to verify whether the servo system would respond to cylinder control signal from the tilt gauge. The tilt gauge applied to the test could measure tilting angle in +/- 5 degree and had angle sensor that generated up to +/- 5V voltage in proportion to change in slope to measure tilting angle in two directions (X—Y direction).

The tilt gauge was attached to the top of the pilot type leader and control algorithm designed to operate cylinder in real time in opposite direction to the one in which the sensor was tilted. (**Figure 7**) The sensor sensitivity was set to 0.1ms and the cylinder speed less than 10mm/sec to prevent unintended movement of the pilot type when the cylinder was operated abruptly.

3) System Operation Test

Figure 7. Tilt Gauge & Servo Valve Function Test

Objective of the 3rd test was to find how the servo system adopting the control algorithm applied up to the 2nd test with interface to tilt gauge would measure and control leader behavior automatically while a pile hole was being bored by auger to which the 2nd test algorithm is applied. Unlike the foregoing functional tests, the pile driving rig was controlled purely by the servo system without human interference in the 3rd test.

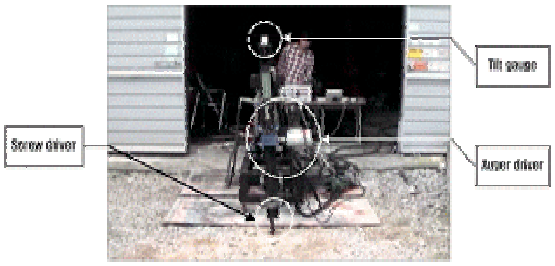

Figure 8. Pilot Type Operation Test

A series of tasks that the tilt gauge detected leader verticality error and sent command to the servo valve to control leader verticality was performed automatically. **(Figure 8)** Hydraulic pressure was applied at 210kg/cm^2 which was equal to the one used in actual working environment.

3.3 Derivation of Prototype Design Parameters

During the 3 rounds of laboratory tests, the following prototype design parameters were derived.

In terms of hardware, it seems sensible to set the bore of cylinder to 100mm and its stroke to 120mm given that the cylinder is mounted on pile driver. The hydraulic volume to be applied seems sensible at 50L/min and the hydraulic pressure at 210kg/cm^2. The pilot type adopted linear transducer as cylinder sensor, but, it would be better for the prototype to use feedback from tilt gauge rather than linear transducer that might have durability problem when mounted on actual pile drivers.

The tilt gauge to be applied should be capable of measuring tilting angle in +/-5 degree, but the actual operational range would be in +/-3 degree and analogue output of +/- 5V as default, considering that if the leader is tilted at an angle beyond +/-3 degree, pile driver would be prone to overturning.

Table 4. Comparison between Pilot Type & Proto Type

Equipment				Pilot type	Prototype
Hardware	Cylinder	Cylinder type		Hydraulic servo cylinder	Hydraulic servo cylinder
		Cylinder size	Bore	38 mm	100 mm
			Stroke	400 mm	120 mm
		Cylinder speed		10 m/sec	10 m/sec
		Hydraulic pressure	Min.	20 kg/cm2	20 kg/cm2
			Max.	210 kg/cm2	210 kg/cm2
		Hydraulic volume		30 L/min	50 L/min
	Servo valve	Hydraulic pressure available		210 kg/cm2	210 kg/cm2
		Hydraulic volume available		30 L/min	50 L/min
		Frequency		15 Mhz	15 Mhz
	Tilt gauge	Measurement Limit		+/– 5 degree	+/– 3 degree
		Sensor sensitivity		0.1 ms	0.1 ms
	Feedback mechanism	Linear transducer	Voltage measurement	+/– 10 V	Feedback from Tilt gauge
	Controller	CPU type		Intel CPM8401	Intel 8051
Software	Equipment control			C	C

Servo valve rated at 50L/min, 210kg/cm^2 and operational frequency of 15Hz (when phase delay is less than 5%) seems desirable given the cylinder volume.

In terms of software, it was found in the test that the industrial computer applied to the pilot type could be applied to the prototype as well, however, Intel 8051 series CPU Chip is deemed to be more desirable to reduce size/weight of the entire system. It seems also sensible to develop a custom control application with C language.

4. Summary & Further Researches

Conclusions of this research and tasks to be followed in the future are:

(1) This research developed pilot type automated verticality measurement/control equipment for PHC piles. To that end, as-is verticality measurement/cont rol arrangement status was investigated, applicable technologies available in Korea and abroad were analyzed, conceptual design was proposed, pilot type was designed and performance test was conducted.

(2) This research analyzed technical feasibility of the proposed system by developing & testing its pilot type as the 1st year assignment in a 3-year R&D program. As a result, technical feasibility of servo system and advanced sensing technology applied to as-is pile drivers to measure and control verticality automatically was proven.

(3) This research plans to develop a prototype based on design parameters identified in pilot type performance test. All technical elements adopted by the prototype to be developed will be applied to as-is pile drivers to test technical feasibility in field environment and economic viability of the proposed equipment will be analyzed as well.

ACKNOWLEDGEMENTS

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A DEVELOPMENT OF STEWART PLATFORM BASED PIPE MANIPULATOR

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Abstract

The concrete pipe laying works are conducted in most of the construction sites. Several automated systems for the pipe laying works have been developed in advanced countries to improve productivity, safety, and quality, and to gain potential savings in costs. They mainly focused upon easy handling and clamping system for the pipes. The major objective of this research is to develop the stewart platform based teleoperated pipe manipulator prototype and to evaluate technical feasibility and productivity analysis of the system.

Keywords: concrete pipes, pipe installation, stewart platform, pipe manipulator, robot, construction automation

1 INTRODUCTION

Hume concrete pipes are commonly used for rainwater and sewage draining works in domestic and overseas construction. Workers are usually exposed to fatal accidents because they need to enter into the trench in order to install pipes. Increasing labor costs makes it hard to keep economic efficiency. However, the construction methods for pipe laying have not been improved over the years. For example, a hume concrete pipe of 800 ㎜ in diameter weighs about 1.2 ton or more. There is potential danger, which is being caught in between materials or being hit by them during handling such heavy materials. The conventional construction method requires simple repetitive works, and quality of finished work is influenced by the experience and skill of workers. A new technical approach, the automated or teleoperated system, could be a challenging way to resolve the above issues.

The major objective of this research is to develop the stewart platform based teleoperated pipe manipulator prototype and to evaluate technical feasibility and productivity analysis of the system.

The major contents and procedure of the research are as follows:

- literature review on pipe installation and robotics
- investigation of pipe installation operation and productivity analysis
- configuration, design, and fabrication of the prototype
- field tests of the prototype
- feasible performance evaluation of the prototype

2. CURRENT OUTCOMES ON THE TOPIC

Several researches concerning the pipe laying works have been conducted in advanced countries to improve productivity and quality as well as safety, and to gain potential savings in costs. They mainly focused upon easy handling and clamping system for the pipes. The conventional pipe installation process is analyzed in order to identify the potential problems from safety and productivity point of view.

2.1 Current Research and Development

NEURAL NETWORK BASED IDENTIFICATION OF NINE ELASTIC CONSTANTS OF AN ORTHOTROPIC MATERIAL FROM A SINGLE STRUCTURAL TEST

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Abstract: In this paper, a new methodology for identifying numerous elastic parameters of an orthotropic material from a single structural test is presented. At the heart of the methodology is the self-learning algorithm which is to extract various stress-strain relationships from a single structural test and train a neural network with the relationships in finite element framework. The constitutive matrix resulting from the trained neural network based constitutive model (NNCM) is compared with the conventional constitutive matrix for an orthotropic material to determine the nine independent elastic constants. An example is given for better understanding of the methodology proposed.

Keywords: neural networks, constitutive relationship, orthotropic material, material identification. self-learning algorithm.

1. INTRODUCTION

Laboratory tests on specimens of anisotropic material such as fractured rocks are carried out to assess their in-situ properties. Mechanical parameters such as elastic moduli and strengths in tension and compression are required by engineers to analyse the structure and develop an economic retrofitting strategy. Numerous large specimens are required to be tested so that the variability of anisotropic properties can be taken into consideration. This may then lead to scarring of the structure and may sometimes be detrimental to structural stability. In any case, the procedure is not only expensive but also time consuming. In this paper the authors demonstrate a new methodology in which the orthotropic elastic parameters can be obtained by monitoring displacement induced by applying a load on the structure at a convenient location. This is a classical 'inverse' problem, which in the past has been solved by many researchers using conventional back analyses for the identification of elastic and strength parameters for isotropic materials [1-3]. However, it is not a simple extension of known procedures if parameters for an anisotropic or even an orthotropic material were to be identified. There have been a number of applications of tools of artificial intelligence for the identification of material parameters from the case histories of monitored data for structures as well as tunnels using neural networks [4, 5]. However, the assumption of isotropy is inherent in these applications.

In this paper, a new two-step methodology is proposed in which, in the first step, the monitored data of a structure are used to recursively train a neural network based constitutive model (NNCM) embedded in a finite element code and in the second step, the required material parameters are computed from the trained NNCM through 'virtual' tests on specimens having appropriate boundary and loading conditions. Although the example given is that of linear orthotropic material, the procedure is generic and applicable to anisotropic nonlinear elastic materials as well.

2. METHODOLOGY OF IDENTIFICATION OF PARAMETERS FROM A TRAINED NNCM

Numerous applications of tools of artificial intelligence to engineering problems are currently being reported by various reseachers. A neural network attempts to find a pattern between 'causes' and 'effects'. If we consider an application to material models in the context of finite element modelling, the components of strain become 'causes' whilst resulting stresses are deemed as the 'effects'. Strain and stress vectors,

$$\begin{aligned} \boldsymbol{\varepsilon}_i &= \{\varepsilon_1, \varepsilon_2, \varepsilon_3, \gamma_{12}, \gamma_{23}, \gamma_{31}\}, \\ \boldsymbol{\sigma}_k &= \{\sigma_1, \sigma_2, \sigma_3, \tau_{12}, \tau_{23}, \tau_{31}\}, \end{aligned} \tag{1}$$

are introduced as input nodes, o_i and output nodes, o_k of the NN, respectively. Then, in the neural network nomenclature, stress-strain relation can be represented as

$$\sigma_k = NN(\varepsilon_i)\,. \qquad (2)$$

The optimal architecture of the NN adopted is shown in Figure 1. It has 6 nodes each in input and output layers. There are two hidden layers with 12 nodes in each of the layers. Thus, the neural network can be designated as NN(6-12-12-6). The first derivative of the NN, DNN_{ik} becomes the so called 'tangential stiffness' matrix for a material at a certain given strain state, $\boldsymbol{\varepsilon}_i$. It can be written as follows:

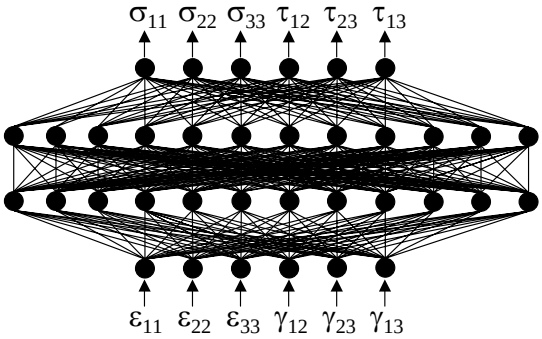

Figure 1. Optimal architecture of the NNCM.

$$D_{NN} = DNN_{ik}(\boldsymbol{\varepsilon}_i, \boldsymbol{\sigma}_k) = \frac{\partial \boldsymbol{\sigma}_k}{\partial \boldsymbol{\varepsilon}_i}\,. \qquad (3)$$

A formulation to compute accurately the first deritave of a NN has recently been developed by the authors [6,7]. Eq. (3) can be applied in both linear and nonlinear range. NNCMs do not invoke a-priori any mathematical constitutive framework. There is also no assumption of isotropy. Therefore, once a NN has been trained for a material, stresses corresponding to any level of strains can be readily computed from Eq. (2). Moreover, a derivative, D_{NN} can be composed at the same level of strain using Eq. (3). The constitutive matrix resulting from the NNCM can then be directly incorporated in a conventional FE analysis code in place of the conventional mathematical theory based constitutive models. Furthermore, with the NN based constitutive matrix it becomes possible to use a NNCM in incremental form of stresses for structural analysis although the NNCM may have initially been trained with the data in the form of total strains and corresponding stresses.

The size of D_{NN} for three-dimensional analysis is the same as a normal constitutive matrix (i.e. 6×6). The computed D_{NN} is generally non-symmetric. It is symmetrised by averaging the off diagonal terms. Comparison of each component of the general elasticity matrix with the computed D_{NN} is made to set up a system of simultaneous equations. This leads to identification of 21 anisotropic independent constants for the general case and nine constants (i.e. E_x, E_y, E_z, ν_{xy}, ν_{yz}, ν_{xz}, G_{xy}, G_{yz}, G_{xz}) for the orthotropic case.

3. TRAINING OF A NNCM FROM MONITORED DATA OF LOAD VERSUS DISPLACEMENT (1)

A NNCM can obviously be trained with the experimental data of stress versus strain. It has been recently demonstrated by Ghaboussi et al. (1998) and Shin and Pande (2000) that NNCMs can also be trained through incremental load-displacement data monitored at several points on the structure; many or all of these points may well be on the surface or the boundary for convenience. Here, a NNCM is embedded in a finite element code and a nonlinear incremental analysis of the boundary value problem is carried out using a 'pre-primed' NNCM (an arbitrary linear tangential stiffness matrix, for example). This gives the computed displacement field from which a vector of displacements for the monitored points (δ_c^n) can be assembled. This would obviously differ from the displacements observed since an arbitrary constitutive matrix was adopted to start the iterative process. In the following step, the same boundary value problem is re-solved in which discrepancy in measured and computed displacements is applied as prescribed displacements. The stresses and strains at each Gauss point and at each increment constitute a set of data for training of the NNCM. The NNCM is recursively trained until the an indicator of discrepancy between predicted and monitored displacement fields, ξ, defined by

$$\xi = \frac{1}{l \times k} \sum_{n=1}^{l} \sum_{i=1}^{k} \left(\left| \delta_m^i - \delta_c^i \right| \Big/ \left| \delta_m^i \right| \right)_n \qquad (4)$$

is less than a prescribed acceptable value. In the above equation, l and k are the number of total load increments and monitoring points, respectively. And δ_m^i and δ_c^i are monitored and calculated displacements at ith monitoring points, respectively.

Thus, at the end of the iterative process, the constitutive model embedded in the FE code is such that it predicts the monitored displacements. A flow diagram of the computational algorithm can be found in [6]. The finite element code which has a NNCM embedded in it has been termed by the authors as a 'self-learning' code since it has the capability to update its constitutive model.

If there are sufficient number of strategically placed monitoring points, it can be assumed that the NNCM is sufficiently trained to predict stress-strain response under arbitrary stress paths. A derivative of the trained NNCM, leads to the evaluation of linear or nonlinear elastic constants at any strain level.

4. AN ILLUSTRATIVE EXAMPLE

For heuristic purposes, a simple structure viz. a plane stress panel with a circular hole at its contre is chosen. The panel which is assumed to be made of an orthotropic material with known principal material axes. Figure 2 shows the geometry, boundary and loading conditions. It is well known that severe stress concentrations take place around the cavilty. A number of monitoring points at convenient locations have to be chosen. It is obvious that larger the number of monitoring points more accurate stress-strain relation can be extracted from the NNCM. Although, collecting data for a large number of monitoring points may lead to higher costs, it should be noted that modern instrumentation techniques with automatic data-loggers make such field measurements relatively easy to conduct.

The authors, at this stage, did not wish to divert their attention to a field measurement programme to obtain monitored displacement data. It was therefore decided to carry out a conventional 3-D FE analysis of the panel configuration using assumed values of the nine independent orthotropic elastic constants as given in Table 1. A three-dimensional analysis, instead of a two dimensional plane stress analysis, was intentionally carried out so as to prove that the methodology is generic and elastic parameters can be identified from displacement – load data of arbitrary shaped bodies. A quarter symmetric model was discretised with 578 nodes and 70 isoparametric 20 noded brick elements[1]. Displacements of 66 nodes on the surface of the model at 5 load levels, resulting from the FE analysis were assumed as physically measured data from the field test, although a much smaller number of monitoring points would be adequate as shown by Shin and Pande (2000). These are the only data needed for training the NNCM embedded in the self-learning FE code. It is noted that although the material is linear with proportional load-displacement relationship, the NNCM cannot recognise this unless incremental data are given.

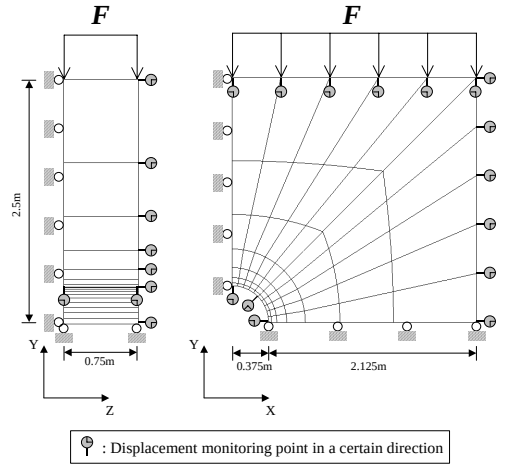

Figure 2. A panel with circular cavity at its centre.

Table 1. Arbitrarily chosen orthotropic elastic constants.

Elastic constants	Assumed values
E_x (MPa)	650.4
E_y (MPa)	967
E_z (MPa)	1735.4
G_{xy} (MPa)	582.2
G_{yz} (MPa)	203.6
G_{xz} (MPa)	694.5
ν_{xy}	0.269
ν_{yz}	0.139
ν_{xz}	0.13

As mentioned in section 3, some initial data are required for 'priming' the NNCM. In this example, the values of isotropic elastic constants, E = 1.0 GPa and ν = 0.2 were arbitrarily adopted for priming. At the 3rd cycle of self-learning process, the overall discrepency between predicted and monitored displacement field reduced from 37.21% to 2.76%.

4.1. Identification of orthotropic elastic constants

At the beginning of each iteration of the self-learning FE analysis, constitutive matrices at all Gauss points are computed using Eq. (3). These are compared to the form of the conventional orthotropic elasticity matrix as the material assumed for this example is an orthotropic material with material axis coinciding with the axis of the model. The elastic constants are simply determined by forming a set of equations with elastic parameters as unknowns. It is noted that NN based constitutive matrices do not invoke any symmetry and as many as 36 elastic constants can be evaluated.

The elastic constants are evaluated at the middle of each load increments of each cycle of the self-learning procedure. Table 2 shows the evolution of nine orthotropic elastic constants with the number of cycles of re-training of the NNCM embedded in the FE code. At the 3rd cycle of self-learning process all the values of the orthotropic constants were less than 3.8% in error against the target values. It is found from numerical experiments that in practical problems tested so far no more than five self-learning cycles are required.

5. SUMMARY AND CONCLUSIONS

In this study, a methodology to identify anisotropic material parameters from a single structural test has been proposed. First, a NNCM embedded in a FE code was trained from the load displacement data of

a structural test. In the absence of real load displacement data, load displacement data from a FE analysis based on an assumed orthotropic elastic material model were used. After the 3rd cycle of re-training of the NNCM the nine elastic parameters of the orthotropic material were computed with the maximum error in any parameter being less than 4%.

Table 2. Prediction of orthotropic elastic constants after each self-learning process.

Ratios	Prediction after 1st self-learning	Prediction after 2nd self-learning	Prediction after 3rd self-learning
$E_{x,p} / E_{x,a}$	103.4%	100.06%	100.24%
$E_{y,p} / E_{y,a}$	75.67%	98.55%	99.02%
$E_{z,p} / E_{z,a}$	65.39%	74.63%	103.46%
$G_{xy,p} / G_{xy,a}$	42.82%	69.36%	101.53%
$G_{yz,p} / G_{yz,a}$	108.4%	106.1%	99.95%
$G_{xz,p} / G_{xz,a}$	64.78%	67.86%	102.95%
$\nu_{xy,p} / \nu_{xy,a}$	72.86%	99.63%	101.49%
$\nu_{yz,p} / \nu_{yz,a}$	25.9%	83.45%	99.28%
$\nu_{xz,p} / \nu_{xz,a}$	111.54%	113.85%	96.15%
ξ (%)	37.21%	13.93%	2.76%

Denominators, 'p' and 'a' indicate 'predicted' and 'assumed' values, respectively.

The methodology of parameter identification for anisotropic elastic constants proposed here is valid for fully anisotropic materials having 36 constants although the example of an orthotropic material has been illustrated in this paper. Although, a rather simple test configuration of plane stress panel with a central cavity was used for illustration, the methodology is generic and elastic constants can be identified from instrumented load-displacement data of three-dimensional bodies of arbitrary shape. A procedure for identifying strength parameters as well as elastic constants from a single structural test is currently being investigated. This may lead to a novel method of non-destructive testing.

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NON-TRENCH GUIDED HOLES DRIFTING BY THE STATIC PIN-HOLE METHOD

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Abstract: Now there is a requirement in the simple and reliable, universal and effective systems providing given accuracy of conducting of holes. At creation of commercial plants of the directed lining of holes it is necessary to correlate integrally a design of head gear (HG) and installations as a whole, ways and means of an automatic gauging and management. Again created principles and devices of the directed lining of holes of small diameter a method of static puncture should be based on tall controllability of devices and the control of an actual rule (position) executive HG. The constructed control algorithms allow to detour the obstacles, move in straight and curve trajectories with the specified speed, to decrease the rate of construction's movement, to perform orientation of construction and provide its smooth installation into the projective position.

Keywords: robotization, construction, control algorithms, visual sensor, mobile robots, planning of the robot's movement, kinematics.

1. INTRODUCTION

The control and management are carried out on an actual end result of measurements and are invariant in relation to numerous disturbing affectings. The available information on non-trench to a lining of horizontal technical lines of small diameter not to the full reflects an actual condition of question. Acting norm give only over-all recommendations whenever possible application of ways and methods of obturated passing, that in practice considerably complicates the proved sampling the equipment and production engineering in view of concrete conditions of construction and maintenance of effective and trouble-free manufacture of these works. The executed work provides an opportunity of creation of installations of the directed lining of snake holes with a method of static puncture due to implementation of given accuracy of lining of holes at the least power consumption of process in view of physicomechanical properties of passable soils and fitted for the further automation.

Tool HG or it spacely - orienting handling mechanism (SOHM) directly influence a direction of lining of the hole, therefore research of system «HG - the hole» it is impossible without the analysis of his interactings with passable soil. The directed lining of holes we shall fathom conducting HG on beforehand projected direction with application artificial and the account of natural bending.

2. THEORETICAL AND EXPERIMENTAL RESEARCHES

The purpose of the lead researches will consist in raise of efficiency of the directed lining of snake holes by perfection of designs of installations, fitted for the further automation. The object in view is attained by maintenance of necessary position in space of the connected parts of the kinematic couple underlying SOHM, due to an adjustable difference of angular speeds of her parts and developed; a way of the directed lining of holes; control systems and designs HG with the rational parameters proved by mathematical model of interactings in system «soil - SOHM - HG - beginning - the monitoring system and managements».

HG represents the handling mechanism which designing is not obviously possible without the kinematic and kinetostatistical the analysis. Structural features HG will consist in necessity of management of him in medium inaccessible to a visual study at conservation of tall extent of positioning and accuracy of improvement of the given coordinates of traffic, and also in restriction of its dimensional parameters (according to production engineering of conducting works and parameters of passable holes). Relative motions of parts of mechanical system depend on an aspect of used kinematic couples. The weakest part of all known methods of development of holes is the monitoring system and managements HG.

Thus, there is a necessity of perfection active, controlled on a command, ways of orientation and development of new ways of management by traffic HG, set up on creation of the developing moment or

deflecting force, by change of geometry HG. It is offered to carry out an adjustment of direction HG at the moment of lining of the hole due to maintenance of necessary position in space SOHM by regulating a difference of angular speeds of its connected parts twirled in one or counter directions. Thus the position of target link SOHM is controlled concerning longitudinal axis HG, and a position of an axis of gear – concerning a vertical irrespective of possible turn bore-pipe, being by a gauge length. Processes of bend bore-pipe at its interacting with soil, orientation HG for formation of holes of the given direction and a profile at a rotary drilling and a puncture are identical and can be observed on uniform physical and mathematical models. The reasons of skew HG in the hole - inhomogeneity of physicomechanical properties of soils, design features bore-pipe and HG, and also lapses at work. Among new development creation of deflecting tools on baseline built the small-sized engine is perspectiv.

With the purpose of implementation of controlled lining of holes a lot of hardware components and controlled HG is developed. However practically all of them are developed for conditions of drilling.

The controlled static puncture is a low-cost, however, low-cost and sweeping way of formation of holes with the least power consumption and having the specific habits: an axial load; absence of twirl bore-pipe which rigidity renders essential effect on process of puncture of the hole; non-stationary medium (inhomogeneity of soils); presence of the big deflecting perturbations.

Demands to developed installations of the directed lining of holes by a method of a static puncture are formulated:

– Again created principles and devices of the directed passing of holes should be based on tall controllability of devices;

– The control and management are carried out on an actual end result of measurements and are invariant in relation to numerous disturbing affectings;

– The control action is formed in view of concrete technology requirements to installation and conditions of its work.

For achievement of tall extent of positioning of target link observed SOHM it should have six extents of mobility: five extents of mobility for removing a target link in required coordinates with a high level of accuracy, and one extent of mobility for moving all mechanism along his own spinning ax. (According to production engineering of accomplishment of works on a static puncture, it is carried out by the power device which has been not connected with SOHM). Alternatives of designs SOHM which target part has four extents of mobility as there is no necessity of destruction of an earth file due to twirl SOHM (is not provided twirl of target link at his arrangement on one axis with the case of the mechanism) are possible.

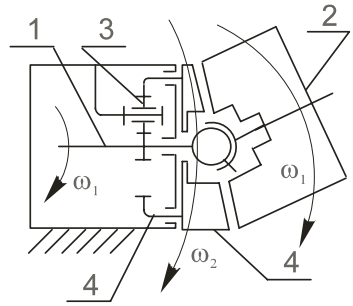
Raise of functionality SOHM is attained by one of three ways:

– with the help of constructive complications of the mechanism on the basis of kinematic couples 5 class-rooms (in basic rotational);

– application of kinematic couples of the higher class-room;

– on the basis of combinations of constructive complications to application of kinematic couples of the higher class-room.

A)



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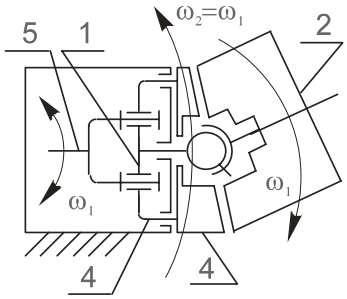
w= 6x4 - 5x3 - 4x1 = 5

B)



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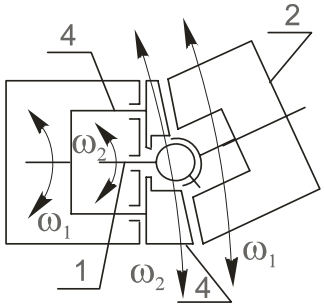
C)



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w= 5

Fig. 1

1 – the cardan shaft; ***2*** – an output link; ***3*** – a gear; ***4*** – a deflecting link, joint with socket; ***5*** – a power shaft, joint with a double free-wheeling clutch; ω_1 – an angular velocity of twirl of cardan shaft (power shaft) and joint with it of deflecting link; ω_2 – an angular velocity of twirl of an output link

Now it is the most expedient to use the third way of raise of functionality of joints. The structural synthesis and the kinematic analysis executive SOHM, and also a synthesis of kinematic couples for the given technology requirements on the basis of the analysis of number of extents of their mobility – ***w*** provide an opportunity of creation of the synthesized hinged system – SOHM, consisting of the minimal number of kinematic couples of the maximum class-rooms. Sampling the kinematic scheme of the mechanism on baseline of two structural formulae is proved: *w = 3 + 2x1 = 5, w = 2 + 2x1 = 4*. Alternatives of designs of handling systems offered on the basis of a synthesis presented on *figure 1*.

For definition of control actions on SOHM problems of kinematic for all suggested alternatives SOHM which look as follows are solved: the direct problem of kinematic will consist in definition of coordinates of an apex of an output link on known importance of an angle of rotation of power shaft of the mechanism; the inverse problem of kinematic provides definition of angular motions of power shaft of the mechanism on a preset position of an apex of an output link.

The analytical decision of problems{tasks} of kinematics for the mechanism represented on *figure 1*, *A)*, looks as follows:

$\text{At}\,\beta_1 > \beta_2$:

$$X = -H\sin\left[2arctg\left(tg\alpha\sin\left(\frac{1}{2}\left(\frac{\delta}{n_1}-\frac{\delta}{n_1 n_2}\right)\right)\right)\right]\cdot$$

$$\cdot\cos\left[\frac{1}{2}\left(\frac{\delta}{n_1}+\frac{\delta}{n_1 n_2}\right)\right],$$

$$Y = -Xtg\left[\frac{1}{2}\left(\frac{\delta}{n_1}+\frac{\delta}{n_1 n_2}\right)\right],$$

$$Z = H\cos\left[2arctg\left(tg\alpha\sin\left(\frac{1}{2}\left(\frac{\delta}{n_1}-\frac{\delta}{n_1 n_2}\right)\right)\right)\right],$$

$$\delta = \frac{2n_1 n_2 arctg\left(\frac{X}{Y}+90^0\right)}{n_2+1},$$

$$\delta = \frac{2n_1 n_2\arcsin\left(\frac{tg\left(\frac{1}{2}\arccos\left(\frac{Z}{H}\right)\right)}{tg\alpha}\right)}{n_2-1};$$

$\text{At}\,\beta_1 < \beta_2$:

$$X = H\sin\left[2arctg\left(tg\alpha\sin\left(\frac{1}{2}\left(\frac{\delta}{n_1 n_2}-\frac{\delta}{n_1}\right)\right)\right)\right]\cdot$$

$$\cdot\cos\left[\frac{1}{2}\left(\frac{\delta}{n_1}+\frac{\delta}{n_1 n_2}\right)\right],$$

$$Y = -Xtg\left[\frac{1}{2}\left(\frac{\delta}{n_1}+\frac{\delta}{n_1 n_2}\right)\right],$$

$$Z = H\cos\left[2arctg\left(tg\alpha\sin\left(\frac{1}{2}\left(\frac{\delta}{n_1 n_2}-\frac{\delta}{n_1}\right)\right)\right)\right],$$

$$\delta = \frac{2n_1 n_2 arctg\left(\frac{X}{Y}-90^0\right)}{n_2+1},$$

$$\delta = \frac{2n_1 n_2\arcsin\left(\frac{tg\left(\frac{1}{2}\arccos\left(\frac{Z}{H}\right)\right)}{tg\alpha}\right)}{1-n_2};$$

Where ***H*** – altitude of an output link on its axis of rotation – distance from the centre of jointing up to an apex of an output link;

n_1, n_2 – reduction rates accordingly the first and second reducers;

δ– an angle of improvement of the drive;

β_1 and β_2– meanings of angular motions accordingly output and deflecting links;

α – an angle of chamier of the combined bases of links of mechanism.

Practically similar dependences are received for other mechanisms represented on figure 1.

Observed SOHM work at small speeds of twirl of links, at interacting to a ground there is a clearing oscillations in transients, in this connection, it is possible to neglect such merit numbers of management, as factor of dynamism (does not exceed 0,5 on oscillograms of pressure at test of an experimental sample of installation), and fixed a time. In the capacity of criterion at sampling parameters the minimal size of linear deviation ***ε*** of targets of an apex of the output link of mechanism from the valid importance is accepted at passage of path during improvement of the drive for realization of these coordinates. The given criterion allows to provide the greatest accuracy of improvement of control action at admissible speed of its realization. The instance of rated path of output link SOHM is reduced on *figure 2*.

By results of accounts it is possible to make the following outputs:

– Sampling optimum critical bucklings designed SOHM and angular velocities of twirl of their links it is possible to achieve high-scale of controllability of designed design with technologically required accuracy figure of improvement of a mechanical

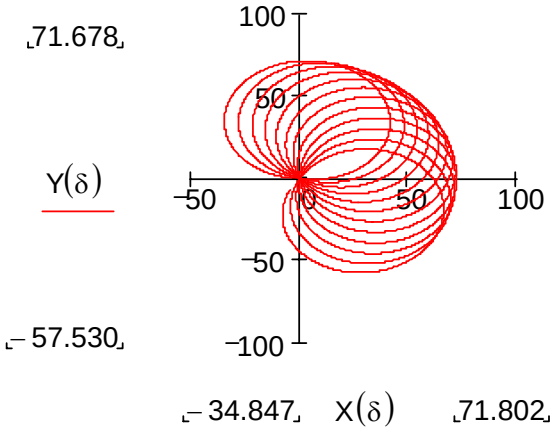

Fig 2.

trajectory, and high-density mechanical trajectories at the minimal size of deviations of the valid path from preset (up to 1,5 mm) can be achieved at observance of condition: $n_1 / n_2 \approx 1$ or $n_2 / n_1 \approx 1$, thus $n_{dv} / n_1 n_2 \geq 3{,}5$ where n_{dv} – engine speed [turn / minute];

– The designed mechanism is effective and simplis in recustomizing. Offered SOHM meet all demands showed to HG for the directed lining of horizontal boreholes by a method of a static puncture;

– The structural synthesis and the kinematic analysis executive SOHM, and also a synthesis of kinematic pairs for preset technology requirements on the basis of the analysis of number of degrees of their movability ensure an opportunity of

Principle of action of an informational - measuring system – IMS and management HG functionally are carried out as follows *(Figure 4)*. Position SOHM concerning axis HG and a position itself HG in a race course of a chink is inspected by four transmitters (inspected sizes are specified in brackets): the displacement pick-up – ***D1*** (a step of introduction L_{IZ}); a transmitter of a

– The necessary position of handle mechanisms, according to new principles of space orientation is ensured with a creation of the synthesized hinged system consisting of the minimal number of kinematic pairs of the higher class-rooms; governed difference of angular velocities of conjugate links of the kinematic pair underlying these mechanisms, at the expense of unidirectional or a up-and-down traffic of their links.

Kinematic configurations suggested controlled HG and presented to dependence of capacity of the built-in electric motor on critical bucklings SOHM on *figure 3*.

vertical – ***D2*** (α_{IZ}); a transmitter of curving HG – ***D3*** (β_{IZ} – corner of an inclination (instead of an antiaircraft corner on vertical chinks), i.e. a corner between a horizontal plane and axis HG and δ_{IZ} – azimuthal a corner); a transmitter of turnovers of engine HG – ***D4*** (n_{DV}). Engineering realization of algorithm of measurement of attitude of axes HG was expressed in development and manufacture of a special transmitter for measurement of an angle of inclination and a bearing angle. After program loading in a

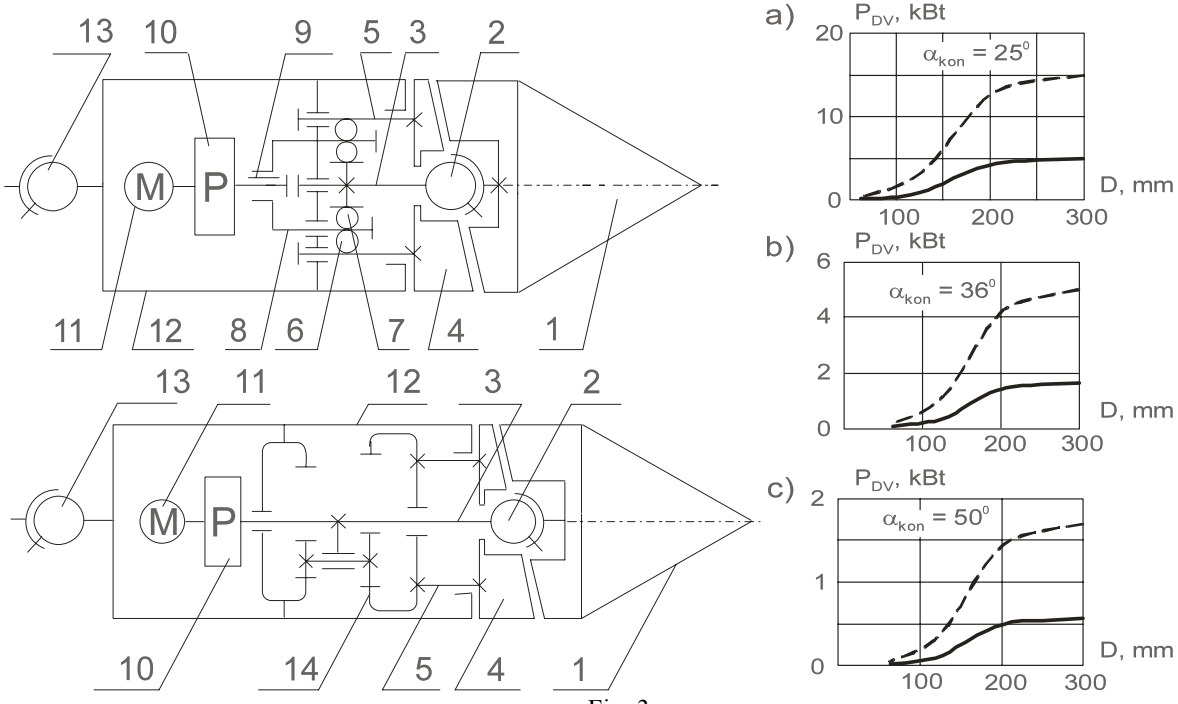

Fig. 3

1 – output link SOHM; ***2*** and ***3*** – a cardan joint and a shaft; ***4*** – deflecting link SOHM; ***5*** – a cartridge clip; ***6*** and ***7*** – free-wheeling clutches; ***8*** – socket; ***9*** – a keyed joint; ***10*** – the reducer; ***11*** – the electric motor; ***12*** – the case; ***13*** – a lens or a joint; ***14*** – the second reducer

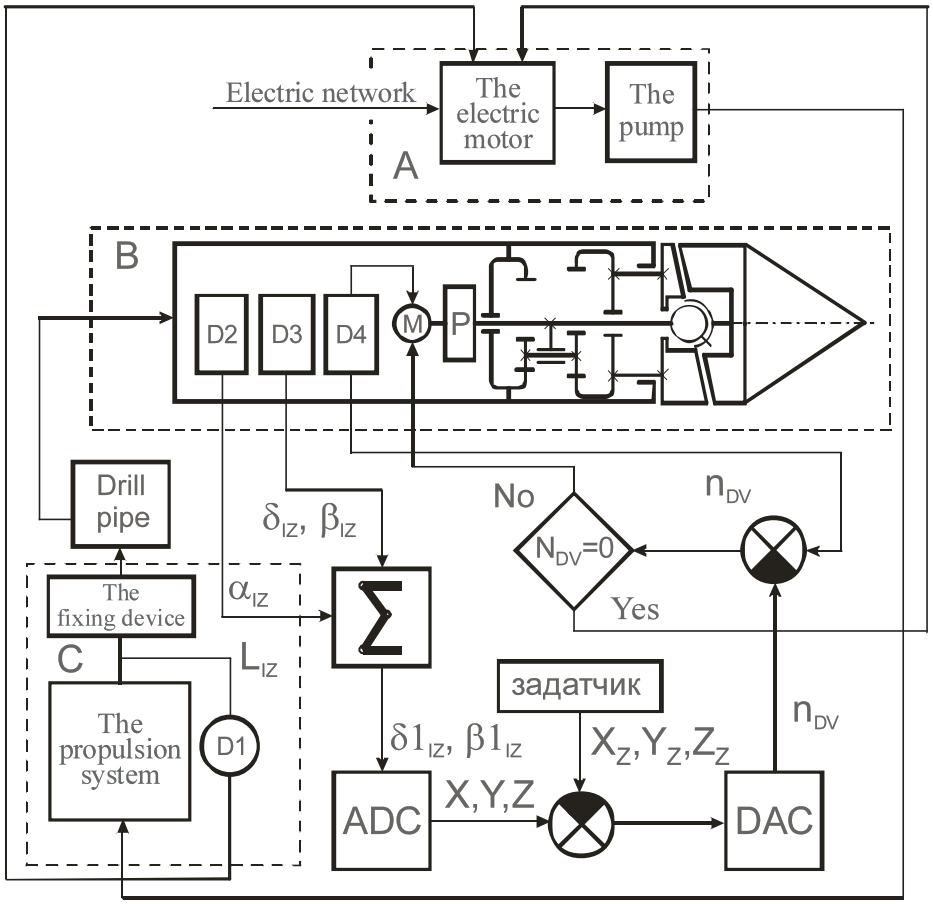

Fig. 4

A – the supply system; ***B*** – the head gear; ***C*** - the propulsion system; ***D1***, ***D2***, ***D3***, ***D4*** – accordingly: the displacement pick-up, verticals, curving HG, a number of revolutions of the drive; α_{IZ}, β_{IZ}, δ_{IZ}, L_{IZ} – inspected sizes accordingly: a bend angle between sections HG, an angle of inclination, a bearing angle, a step of motion HG; ***Σ*** – the adder; ***DAC*** – analog-converter display; ***ADC*** – the analog-digital converter.

computer coordinates of the origin of position HG are established and original indications of transmitter ***D2*** are removed. The power supplies of the powerplant are carried out from a power room or an off-

line system of power supply. Power cylinders, due to the timbered lock on their stocks, introduce beginning with HG in hole mouth. The step prosliders is inspected by displacement pick-up ***D1***. A problem of an artificial bending of hole mouth and saving of a preset direction of a lining executes SOHM HG.

At passage HG of a step prosliders L_{IZ} transmitter ***D1*** gives a signal on the arrangement of switching-off of the engine of the supply system. Then position HG in a race course of a chink by interrogation of transmitters ***D2*** and ***D3*** is defined. Signals from these transmitters in the impulse form act in integrating element where indications of transmitter ***D3*** – meanings β_{IZ} and δ_{IZ} – are adjusted on size α_{IZ} – indications of transmitter ***D2***. The updated meanings $\beta 1_{IZ}$ and $\delta 1_{IZ}$ act in the analog – digital transducer of an analog-digital converter where obtained datas and constant L_{IZ} will be transformed to coordinates ***X***, ***Y***, ***Z*** positions HG. Obtained coordinates are compared with preset – X_Z, Y_Z, Z_Z – the program calculated by a computer proceeding from a prescribed trajectory of a projected line. If targets do not correspond valid on a unbalance signal acting in analog – the converter display – ***DAC***, is calculated necessary engine speed n_{DV} for reorientation SOHM HG so that on the following step prosliders to return HG on a preset line of a lining of a chink. Required meaning of size n_{DV} is compared to the valid meaning interrogation of transmitter ***D4***. If the difference of rated and valid sizes n_{DV} is equal to zero, on the electric motor the signal about turning on of the powerplant and the beginning of passage of the following step prosliders acts. At deriving in a logic network of a unbalance signal – $n_{DV} \neq 0$ electric motor HG reinstalls it SOHM up to a required position, thus the quantity of turnovers of the engine is inspected by transmitter ***D4*** before observance of condition $n_{DV} = 0$. On execution of this operation the signal in the supply system about the beginning of the following step prosliders moves. Obtained indications of transmitters and calculated coordinates of position HG on each step are remembered by a computer, and under these indications the valid line of a chink is under construction.

Experimental researches were carried out in some stages: researches of interactings in system «the instrument – beginning – a ground», researches of process of interacting of the instrument with a ground and tests expirience sample HG containing a built-in control gear and a monitoring system of a position.

In the capacity of plants for holding researches full-scale installations were used, and tests were carried out in actual conditions. As a result of tests it is established:

– Efficiency of agency of critical bucklings HG on a curvature of a path of a chink and a degree of controllability;

– Necessity of management HG for a lining of the directed chinks, for the lack of an opportunity of deriving of rectilinear chinks in the extent more than 8 meters owing to heterogeneity of transited grounds and habits of a natural bending;

– The Opportunity of creation controlled HG and realizations of the accepted way of an adjustment of a direction of its movement.

– Experimental researches have allowed to define dependence of axial effort - $\boldsymbol{P_{OS}}$ = f ($\boldsymbol{H}$, $\boldsymbol{V_{GR}}$) for various geometrical parameters of tips in view of physicomechanical characteristics of a ground. $\boldsymbol{V_{GR}}$ at introduction of a tip it was defined as a difference of volume of a section of a drill pipe in length, equal current length of the paved chink, and volume of the tip introduced into soil - target link SOHM and a drill pipe.

The constructed control algorithms allow to detour the obstacles, move in straight and curve trajectories with the specified speed, to decrease the rate of construction's movement, to perform orientation of construction and provide its smooth installation into the projective position.

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Development of a Revolutionary Advanced Auto-shackle, A Construction Equipment

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Abstract : In the field of construction work, shackle is one of the most essential tools to build up a structure on the foundation. The process of setting up the beam to its up-right position starts from linking the end of the beam and the shackle by a construction worker. Then the beam is carried to the proper place by a crane. After fixing up the beam, according to the old-style process, a construction crew climbs up the beam to release it from the shackle. This step is hazardous and very inefficient, which is needed to be automated. For this reason, the auto shackle controller with two shackles, which can release the beam through a wire-less command, was developed. The auto-shackle controller makes the work safer and more efficient. However, the early auto-shackle controller itself was heavy and had some sorts of problems in safety and durability.

In former research, the advanced auto shackle controllers solved the problem of the durability by reducing the height and the internal mechanical structure of the shackles; the control wires were damaged easily by steel chain hits when the shackles were released. However it is still heavy because the controller uses an automotive battery for a power source. Now, we present a super miniaturized high-performance auto-shackle controller which has no exterior controller using state-of-the-art technologies. Furthermore mechanical structures are changed to ensure the safety of the shackle.

Keywords : Auto-shackle, construction tool, shackle, clamp, revolutionarily advanced auto shackle.

1. INTRODUCTION

For the construction of higher-storied buildings, composing a steel-frame structure is a basic task and a very important step [1]. Figure 1 shows the process of setting up steel frames. In old- style processing, a construction crew binds an iron beam (‘a’ in the Figure 1) to the shackle equipped under the working crane (‘b’ in the Figure 1) and then moves it to the proper place for temporary assembling [2] [3]. Last, the construction crew climbs up to the top of the iron beam to unbind it from the existing bolts and nuts at the shackle (‘c’ in the Figure 1). It is a very hazardous work because of the falling accidents. In addition, it is inefficient because of the climbing time and the increasement in operation loads. It is a serious problem so we need automation in the working processes.

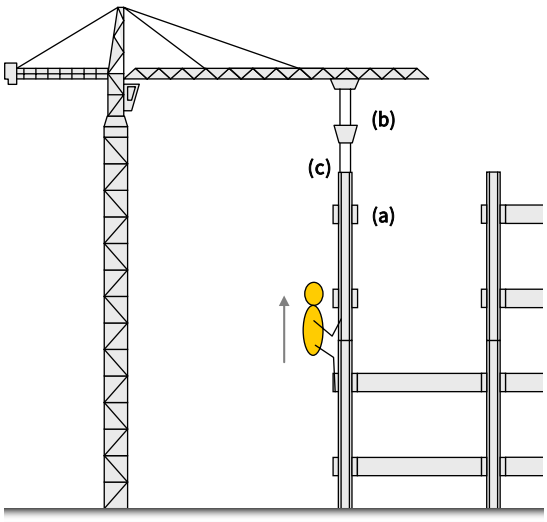

Figure 1. The process of building an iron beam

For this reason, the auto shackle controller with two clamps, which can be operated to release the iron beam through the wireless remote controller, was developed by Research Institute of Technology, Samsung Corporation [4] [5]. Hereby, the auto shackle controller removed the danger of the operation radically. In addition, it reduced cycle time of the iron beam assembly so the work became more efficient.

However, the early auto shackle controller is heavy and has some sorts of problems in safety and durability. To solve these problems, the advanced auto shackle was developed [6] through changing and miniaturizing the structure of the clamp as well as developing a durable controller. Nevertheless, the advanced auto shackle was still heavy because of its power supply which was a vehicle battery. Another problem was breaking of the signal wires. As battery technology makes progress, the super miniaturized high-performance advanced auto shackle controller which has no external controller is designed to solve these problems radically. As battery technology advances, the auto shackle miniaturizes revolutionarily. Because of structural change, safety and durability increases. Thus, the super miniaturized auto shackle will be used commonly.

2. THE FIRST AUTO SHACKLE CONTROLLER

Equipments like a tower crane is usually used for setting up an iron beam for the foundation of high-storied structure. The crane equipped with a shackle and sling wires carries the beam to the proper place for the foundation. The old process is that a crew climbs up to the top of the iron beam and releases the clamps by hand. This step is very dangerous. The first auto shackle which was developed by Samsung Corporation, releases a steel beam automatically with wireless communication controller instead of the old process. It makes the working process more automatic, efficient and also prevents falling accidents. It is an epochal equipment to the new working process.

Figure 2. Setting up a vertical beam

Figure 2 is using the first auto shackle in the construction site of the Hopping power plant in Taiwan. In this figure, there are clamps of the auto shackle on the top of steel beam. The arrow points at the main body of the auto shackle.

2.1 Sturcture of the first auto shackle

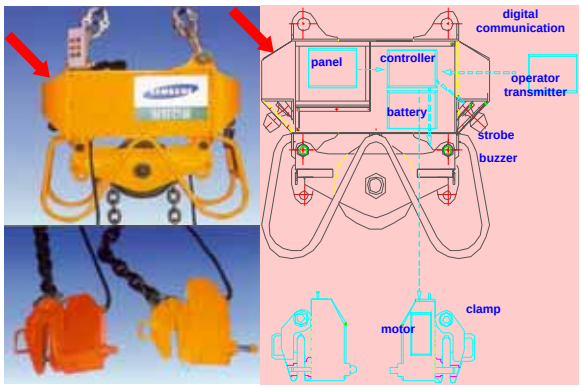

Figure 3. The first auto shckle

The first auto shackle controller primarily consists of the main body and two clamps. Each of the structure is like Figure 3.

2.1.1 The main body of the first auto shackle

The main body which is pointed by an arrow has a rechargeable battery for the power supply of this system, wireless communication module and system control board are built in it. The main body prevents damage from the outside impact and humidity like the function of a cabinet and transmits the weight of suspended steel frame to the crane. Also, it gives sounds and lights alarms of its operation states to surrounding crews.

Table 1. Properties of plates

Material	Elastic constant	Tensile strength	Yield point	Remark
SM45C	2.1×10^4	42.5	35.0	$\nu = 0.29$
SCM415	2.7×10^4	85.0	39.0	
SNCM439	3.7×10^4	75.9	48.1	

A steel plate is attached inside of the main body because the wrapping material of the main body can not stand the weight of a steel frame. The steel plate is made of SM45C [7]. Thirty millimeter of armature is welded into the parts which can break down because of concetration of the stress of the frame. In the edge which is an expectable concentration of the stress, breakdown stress is $35 kgf / mm^2$ and the stress state of Von Milses [8] is $11.3 kgf / mm^2$. Table 1 is the summarized properties of plates.

In the part of bolts and chain linking, the sectional stress concentration is likely to happen so the SNCM

bushing is installed and heat treatment has done. Thus, the possibility of breakdown is reduced.

2.1.2 System controller

The controller consists of wireless communication module, a digital indicator for expressing operation state and input device to command digital and analogue input.

The wireless module of auto shackle is BIM-433-HP manufactured by RadioMatrix, using this module interfaces with a microcontroller. Also, to communicate by wire, a port is made up with MAX-232.

A limit switch is used for the crews to detect the locking state of the shackle pin. The control program interprets and analyzes operation state with the limit switch signal.

2.2 The clamp of the first auto shackle

The clamp is the actual part of linking the shackle to a steel beam. It performs two major roles in the whole system. The first role is hanging an iron beam. During that time, the clamp pin has to stand the high pressure of the steel beam's weight so the pin is made from the strong material SNCM. Except the pin, expectable parts of high stress transmission is made from SCM in the whole clamp.

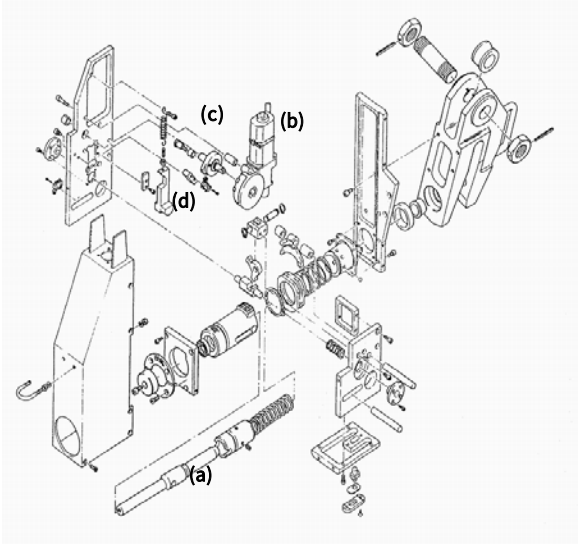

Figure 4. Deal drawing of the first auto shackle clamp

Figure 4 is the deal drawing of the first auto shackle clamp. The pin ('a' in Figure 4) receives elastic force of the spring, to the outside of the clamp, which is the position open. To lock the shackle, a crew has to press the pin inside the clamp. The auto shackle operates automatically for the unlocking process to minimize its power consumption so the locking process is manual. The DC motor ('b' in Figure 4) in the clamp is served to release the clamp. The cam ('c' in Figure 4) is moved with dynamic force of the motor to press the trigger. Then, the pin is released by the elastic force of the spring. The method of the locking tool is double lock for safety.

The main body links two clamps with chain. Two signal lines along with the chain let clamps communicate with the controller in the main body. In the whole processing of the first auto shackle controller, there is danger of breaking the signal line because the signal line gets tangled with the chain. For this reason, Figure 4 shows that the motor part leans twenty degree form the locking part to protect the breaking the wire.

2.3 Wireless communication

In 2.1, the auto shackle consists of two major parts which are main body and clamps. In addition, the wireless communication part is one of the auto shackle parts. In general, the kernel of wireless communication technology is to minimize noises and jamming. The first auto shackle controller removes the possibilities of noises and jamming with digital telecommunication method.

The wireless communication module of the auto shackle consists of two major parts. They are transmitting and receiving parts. The transmitting part is built in the remote controller to make it easy to manipulate. The transmitting part receives and analyzes digital signals and then it transmits the signal to the PCB for control input.

The remote controller has six buttons and three indicating lamps. They are power ON/OFF buttons and releasing A and B buttons, each of that works to release A and B clamp. The A and B buttons work when they are pressed at the same time to prevent incorrect controls. The indicating lamps consist of power ON/OFF state lamps and battery recharge state lamp.

Table 2 is specified summary of the wireless communication.

Table 2. RF modem specification

RF - Modem Description	TX - UNIT	RX - UNIT
Frequency	447.8625 ~ 447.9875 kHz	
Channel Frequency	12.5 kHz, 11 chn	
Modulation	FSK	
Communication Speed	2400 bps	
Service Distance	100 m	

2.4 Effects of the first auto shackle

The first auto shackle controller secures safety of the crews and gives economical effects as shown in Table 3 under nomal working environment.

In Table 3, Safety of crews is remarkably increased and the time cycle of processing is decreased using the auto shackle. As a result, productivity is increased.

The economical efficiency can change from twenty

to forty percent by the working environment. In Table 3, the data does not include immaterial effects of supporting equipment like tower crane and prevention of accidents.

Table 3. Comparence of processing time

Item	Crew handling	Using auto shackle	Effects
Standard operation hour	8.5 hour/Day		
Time Cycle (min/cycle)	30	23	Reducing 7
Number of operation/Day	17	22	Reducing 5
Construct period (T site : 500 operations)	29 Day	22 Day	Reducing 7 days (Reducing about 24%)
Safety	Danger	Safe	Removing danger source

3. THE ADVANCED AUTO SHACKLE CONTROLLER

3.1 Problems of the first auto shackle controller

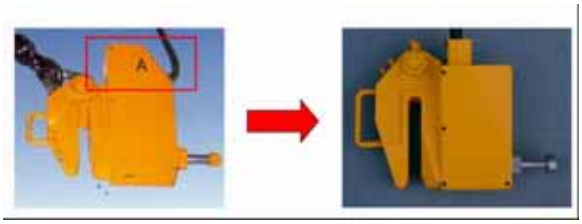

Figure 5. Formal change of clamp

The first auto shackle does not have enough distance between connecting part and operation equipment as the Figure 5 area A. When a crew unlocks the auto shackle, he should worry about damage of signal line due to crash with the chain by strong elastic force and inertia of the clamp. The motor position of the first auto shackle controller is controlled by limit switch so it is not durable. The weight of clamp is heavy so the restoration elastic force of the clamp is strong too. Thus, a crew sometimes needs supporting equipment when he locks the clamp. In the wireless communication part, the operator of the shackle does not know the present position of motor. If the limit switch is broken, motor works continuously. That could be a cause of motor breaking.

These problems are possible to solve by reconstructing the motor parts position that reduces the size of the clamp and developing of reliable controller. Also, operator of the shackle can know the present motor position through wireless communication when the limit switch is broken.

3.2 Advanced auto shackle controller

Figure 5 shows miniaturization of the clamp to cut the upper motor part. The structure of motor part is changed too.

3.2.1 Structural change of advanced auto shackle clamp

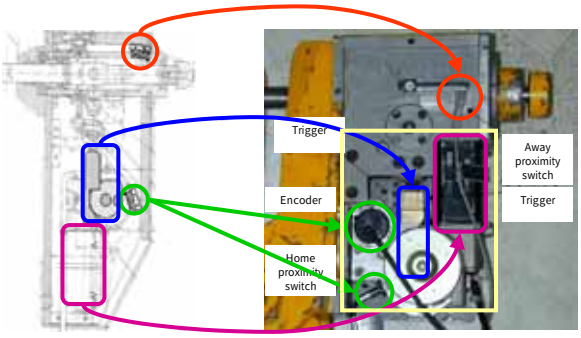

Figure 6. Structural change of advanced auto shackle clamp

In Figure 6, we can see that not only the appearance but also the structure of main body is changed in order to solve the problem commented in 3.1. In the first auto shackle, motor power was transmitted through the cam. However, the advanced auto shackle transmits motor power through the crank. An encoder is used to detect the present position of motor, which prevents the motor from excessive working even though the switch detecting locking state is broken.

The type of switch which indicates locking state is proximity switch instead of limit switch. Proximity switch is a metal detecting senor. It is durable and operates well.

3.2.2 Development of a reliable controller

The reliable controller board is developed. It can check the states of wireless communication, encoder and proximity sensor by itself. It can also report the present state of the auto shackle with a buzzer and alarm lamps. In addition, developing the remote controller which notifies the state of the auto shackle makes the auto shackle more reliable.

3.3 The shackle open process of the advanced auto shackle controller

The shackle open process is as presented next. There is a big load to begin initial operation so motor is controlled with full power instead of PID control. At first, unlocking angle is chosen to be 110 degrees and then, controller commands the motor to rotate 110 degrees. If the motor rotates less than 90 degrees it means the clamp at the shackle is still locked. At that time, controller commands that the motor rotates 10 degrees counterclockwise. And then the controller commands that the motor rotates clockwise again. This process repeats 15 times.

When the clamp is unlocked, “Away proximity switch” turns ON. If the switch doesn’t turn ON,

controller regards that the clamp is lock and gives the switch error.

After finishing the unlocking process of the clamps, the motor returns to the original position then, the “Home proximity switch” turns ON. After finishing the unlocking process, motor turns ON the buzzer to notify working state.

4. THE REVOLUTIONARY ADVANCED AUTO SHACKLE CONTROLLER

4.1 Problems of the advanced auto shackle controller

After developing the advanced auto shackle controller, some sorts of problems of the first auto shackle controller was solved. However, some problems of safety and durability which, the first and the advanced auto shackle controller have still remained.

Early auto shackle controllers have structural problems. The pin of clamp protrudes from the inside clamp. When crews lock the clamp, they should push the pin inside of the clamp. If the clamp is broken, the pin is pushed outside by the elastic force of the spring. It became a problem of stability. Also, the signal line between main body and clamp is rubber cable. It made possible the danger of the wire breaking because of a strong elastic force during unlocking process.

The reason of heavy weight of early auto shackle controller is the power supply in its main body. It is a vehicle battery and it is large so the main body is made to exist. The main body has a steel plate because it has to withstand the weight of hanging steel beam. Main body weighs 500kg. Each clamp weighs 30kg. Thus, the weight of early auto shackle controller including linking chain is approximately 600kg. Because of that crews can not link it to a tower crane by themselves. Because of the weight of auto shackle controller, the crew sometimes needs some equipment.

For this reason, the revolutionary advanced auto shackle controller is designed.

4.2 The structure of revolutionary advanced auto shackle controller

Figure 7 compares early auto shackle controller with revolutionary one. In appearance, there is no exterior controller but only chain and two clamps. The signal lines disappeared because controller is placed in the interior of clamp. Also we can remove the steel plate which withstands the weight of the steel beam.

As the main body disappears, the whole weight of the auto shackle controller becomes approximately 60kg. As a result, crews can link the auto shackle controller to a crane without any equipment.

One of the reasons why the auto shackle is revolutionarily light is changing battery. Lithium-Polymer battery [9] is used for power supply instead of vehicle battery. In the case of motor, motor controller and other devices in the main body are miniaturized and organized in the clamp.

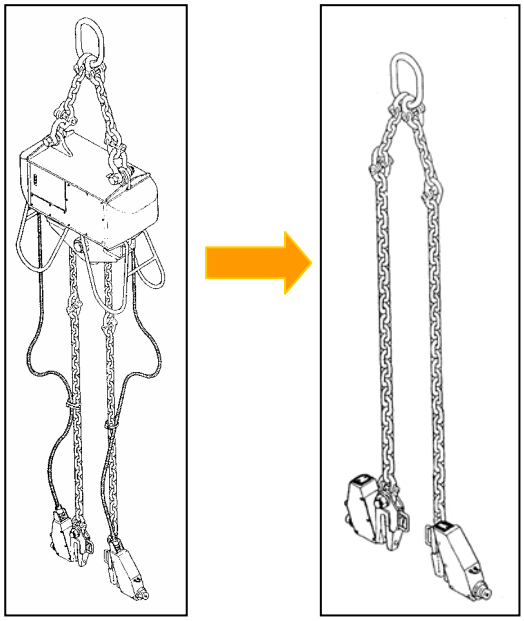

Figure 7. The revolutionary advanced auto shackle controller

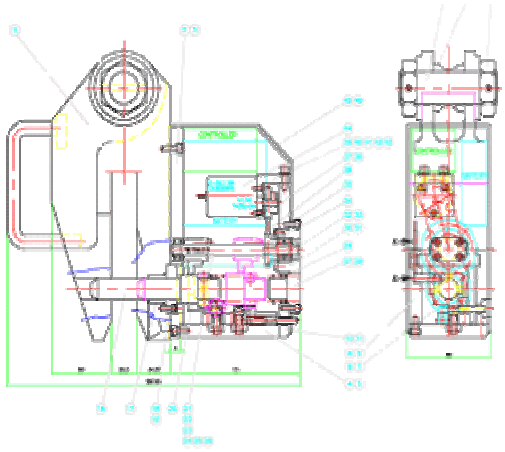

Figure 8. The drawing of the super miniaturized auto shackle

Figure 8 is the drawing of the super miniaturized auto shackle. It shows miniaturized battery. Motor controller is also minimized. It shows the initial state of the revolutionary advanced auto shackle pin that is locked. If the clamp is out of order, the pin does not unlock by itself.

The unlocking operation is changed structurally. The early auto shackles use the elastic force of the spring. However, the revolutionary advanced auto shackle has a different working structure. Rotary motion of the motor is converted into rectilinear motion then the pin is moved slowly instead of using elastic force. The early auto shackles are automatic only on the unlocking process. The revolutionary one

locks and unlocks automatically when the motor rotates clockwise or counterclockwise. The motor part of the clamp is parallel with the locking part. There is no necessity to lean the motor parts because the signal lines disappeared. The side view of Figure 8 shows it.

5. CONCLUSION

In this paper, we presented the background of developing the auto shackle controller which influences automation in the construction field. We presented what is the first auto shackle controller and analyzed the problem of it. We also presented the advanced auto shackle controller which solved the problems of the first auto shackle. However, the advanced one still has problems. Finally, we introduced the design of the super miniaturized high-performance auto shackle controller.

The revolutionary one is developing commonly. Through further research, we can study how to make work in construction fields more efficient and safe.

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ROBOT ORIENTED DESIGN OF REUSABLE PARTITION WALLS WITH INTEGRATED BUILDING AUTOMATION CAPABILITIES

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Abstract: In the long run reusable partitions walls have lower costs and are more economical and especially more variable compared to convenient post-and-beam-structures. Because room requirements – mainly in office and administration building – change faster and faster, an extensive potential on future markets for these technologies exists.

Keywords: Flexibility, Economic Efficiency, Non-supporting removable wall-unity, Media- and electric wiring, Put-and-slide-technology, Relocate systems, Cost, Different Elements, Adapted assembly robot system.

1. INTRODUCTION

A higher and higher flexibility of the floor plan is expected in office- and commercial building as in house building. The change of users or function often results in the wish redesigning the existing spatial pattern. A basic floor plan flexibility often is possible and practiced by dividing the load-bearing building surface from non-structural separation walls and ceilings. A well known system of this type of walls is a wooden or metal post-and-beam-structure with mineral fibre filling and plasterboard panelling. By using this building system it is difficult to realize variations of different room structures and subdivisions by self building. In fact they are cheap to produce and to install but in the end they are much fuss in redesigning, few flexible and actually not reusable. In addition there are already reusable, demountable partition systems available. However they usually are to expensive and to much fuss to construct.

Together with partners from industry, the Department for Building Realization at the University of Technology, Munich, Prof. Dr. Bock, is involved in the development of flexible partitions. The following qualities were defined as important objectives for a viable system:

• The elements should be demountable – without causing damage to the existing structure – and capable of reuse.
• They should have a finished surface on both sides and provide a complete lightweight construction system.
• A maximum of two persons should be able to handle and assemble the elements.
• The elements should provide the boundary conditions to be handled and assembled by an automated device, which will be developed in a following project.
• The price should lie between that for standard plasterboard partitions with metal studs and other existing partition systems.
• The elements should have a simple form of construction that would enable a joiner to carry out repairs.
• It should be possible to incorporate additional functions and fixtures, such as monitors, lamps, shelving, ventilation, etc.

2. ECONOMIC VIABILITY OF EXISTING SYSTEMS

The economic viability of a prefabricated system – in comparison with conventional plasterboard stud partitions – is not determined by the investment costs alone. The costs incurred in the course of its life and the costs it saves compared with other systems also have to be taken into account. The viability of prefabricated systems increases with each reuse.

• With careful planning, the costs of creating the abutments with adjoining sections of a building will be roughly the same for both prefabricated and conventional plasterboard types.
• The surface quality of plasterboard partitions is lower than that of industrially prefabricated systems.
• Finally, savings that offset additional investment will become apparent when prefabricated partitions

are dismantled and reused in a different location. Whereas the cost of relocating a prefabricated partition is about 30 per cent of the investment costs, the cost of removing a plasterboard stud partition and re-erecting it elsewhere amounts to about 150 per cent of the investment costs. The amortization of a wall construction system will, therefore, depend on the number of times it is dismantled and re-erected.

• Other factors to be considered are the economic and environmental costs of disposal. Systems that can be reused have obvious advantages in this respect: they conserve raw materials, reduce building waste and help to avoid disposal charges.

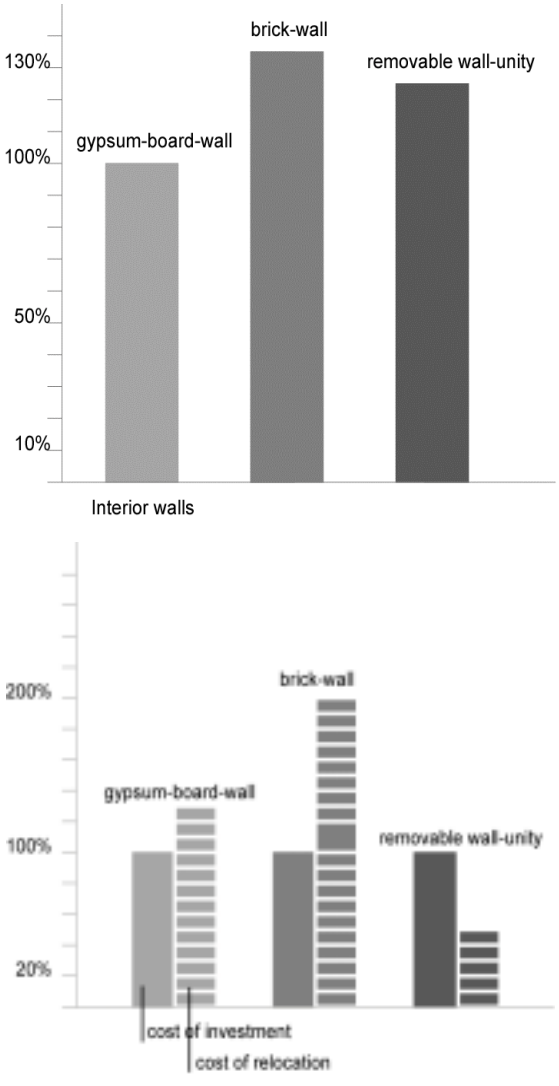

Fig. 1 Interior walls: cost of investment and relocation

3. ELEMENTS

Assuming a sensible separation of the structure and finishings, the geometry of the wall elements will be based on the room height. Various panel widths are possible. Our system is based on a 20 cm module (with unit widths ranging from 20 to 120 cm in 20 cm stages). Although widths above 120 cm are possible, but they are not recommended in view of the weight of elements fulfilling both: human and robots request on maximum load.

In addition to the wall elements, L"- and T-sections are necessary to form angles and intersections. In keeping with the grid dimensions, the legs of these members are 20 cm long. Other system elements include door and clerestory units and end sections.

Fig. 2 Timber-framed partition element, all-glass element

4. CONSTRUCTION

The supporting structure for the individual elements comprises a peripheral frame 70 mm deep. The frame can consist of glued timber or special welded metal sections, cut to mitre at the corners. The rigidity of the frame has to allow dynamic handling with future interior robots. In addition it should provide space for gripping.

Suitable materials for the surface finish include wood sheeting, gypsum fibreboard, glass, etc., which also provide stiffening. A 30 mm soft-fibre layer around the frame improves acoustic insulation in the area of abutments and joints. Abutments with existing structural walls are created with a special section with recessed shadow joints. The individual wall elements are connected to each other by dovetail interlocking members with a self-centring geometry and with integrated plugs and sockets to allow the passage of various media from one element to another.

By the restriction on few standardized construction components an automated manufacturing can be realized easily. With only one pair of fast

connectors, two kinds of frame cross sections (wood and stainless steel) and a standardized cable harness all kinds of elements can be manufactured on only one assembly desk. The surface materials can be varied at will, but at the same time handled with the same vacuum gripper.

5. CONNECTORS

The plastic connectors used in the system under development are produced under licence by the Fischerwerke company. They allow a tight mechanical connection of the wall elements and a simultaneous link-up of all media within the unit, including electricity. Up to three connectors per wall element are possible.

Fig. 3 System connector in timber stud wall

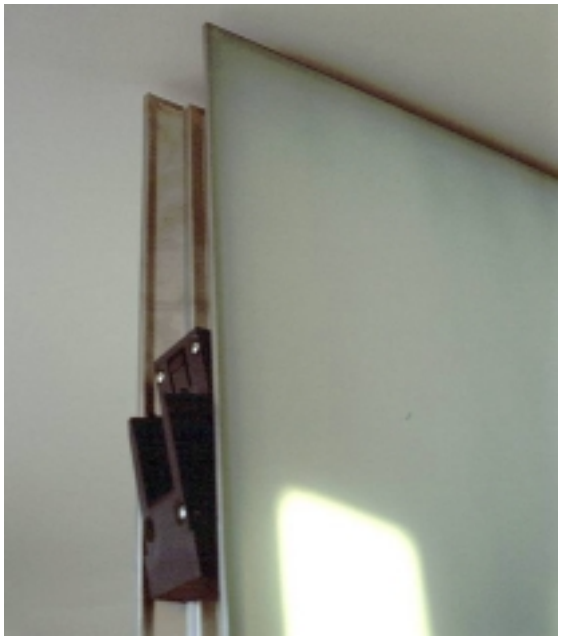

Fig. 4 System connector and soffit abutment

6. THREADED FEET

Every wall element stands on two 15 cm threaded feet fixed in the frame. The feet should be in a retracted position when the element is placed in position. By adjusting the height of the feet, the units can be precisely levelled and raised until they are pressed tightly against the soffit. An adjustment height of up to 11 cm is possible. When one element is fixed in position, the next one can be installed alongside it.

Fig. 5 Floor connection with metal section and adjustable threaded feet

7. ASSEMBLY

Not more than two persons are required to assemble the wall elements. Where a partition abuts a structural wall, the assembly should begin at that end. In the case of a freestanding configuration, the assembly can begin at either end. When the second element is initially placed in position, the two halves of the system connector will be slightly offset to each other. They interlock when the new element is adjusted in height. The same principle applies to the assembly of corner connections and intersections. The erection sequence is concluded by inserting a closing piece in the space at the end. The void between the base of the elements and the floor remains accessible for adjustments and additional installations. It is filled with a sound-insulating mat and closed with a compression strip that forms a flush skirting. To dismantle the wall, the assembly process is simply reversed. The assembly/dismantling time for the present system, is about 15 minutes per element (80 x 240 cm, or roughly two square metre).

By using an adapted assembly robot system this procedure could be overtaken and should halve clock cycle.

The assembly process is very simple and is limited to movements, which can be taken over easily by autonomous robots: Supplying robots can take over the transport of afore calculated element packages to the erection place, while assembly robots determine the assembly position accurate to a millimetre on the basis of Tracking-Systems like

GPS. By the self centring of the fast connectors the position of the next construction component is given. Assembly work hereby also consists in the adjustment of the elements by the vacuum gripper and following in the raising of the feet for the spanning of the wall between flooring and ceiling.

8. ELECTRIC PREINSTALLATION, LED

Special processing of the frame sections allows a preinstallation of electric cables within the elements. Where a transparent surface is desired, the cables can be concealed in the frame. Any switches or socket outlets should ideally be installed during the manufacture of the elements, although they can also be fitted subsequently. Additional cables (e.g. for telephones, computer networks, etc., where connections are less desirable) can be installed in the space at the foot of the elements.
Due to the possibility of reusing the elements, it is worth integrating high grade building automation components. Using bus connection, every type of circuit according to every floor plan variation can be set. Custom-made elements with integrated electronic devices or computing can be fabricated as well.
All-glass models are also possible with sandblasted or coated surfaces and with invisible frames. The glass is adhesive fixed to the frame to create a rigid composite element.
Three-colour LEDs integrated in the bottom of the cavity between the panes permit the elements to be illuminated.
In autumn 2003, a complete office floor divided by these partition elements was installed. By combining red, green and blue devices every colour of light can be adjusted. Thereby the elements can indicate directions or also be integrated into a consistent environment.

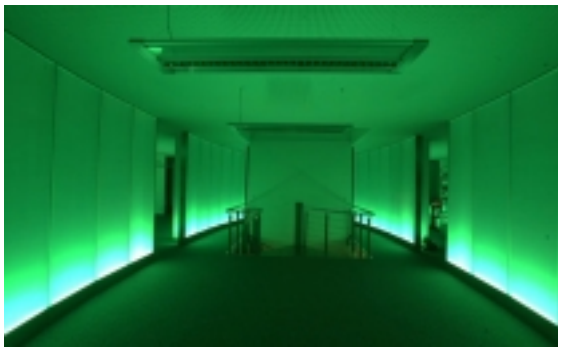

Fig. 6 Partition elements with integrated three-colour LEDs in an office floor

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A MECHATRONIC SLIP ROBOTIC SYSTEM WITH ADAPTIVE CONTROL FOR ERECTING MONOLITH OBJECTS

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Abstract: The paper considers technological features of erecting monolith objects with a variable cross-section, presents the formulated requirements to the mechatronic complex and the principles of its construction and gives the complex structure. Great attention is paid to the problems of the mechatronic complex movements planning taking into account restrictions on control and disturbing influences affecting the structure being erected. In conclusion the paper deals with the problems of forming adaptive laws of for controlling joint coordinates ensuring development of the planned trajectory.

Keywords: monolith construction, slip forms, mechatronic robotic system, planning, control algorithms, visual sensor, mobile robots, planning of the robot's movement, kinematics.

1. INTRODUCTION

Construction of objects for different purposes requires great labour consumption and a number of regulating operations especially for the structures with varying cross-section and wall width. The carried out analysis of the monolith construction technology has shown that it is possible to make a mechatronic robotic system on the basis of slip forms, which provides mechanization and automation of operations. The mechatronic slip robotic system (MSRS) mainly incorporates a moving platform with slip forms and a concreting robot with a programmable control. Later on it is expected to introduce into the system robots for embedding and anchoring reinforcement, it will make possible to automate the whole cycle of erecting monolith structures. Taking into account complexity of the MSRS as a controlled object, a great number of disturbing and adjusting action and restrictions for control it is of interest to solve the problems of the system operation software, planning its movements and developing adaptive laws of control.

2. THE PRINCIPLES OF CREATING A MECHATRONIC SYSTEM

As base objects of MSRS we took into consideration chimneys television and observation towers having conical and hyperbolic cross-sections. The system development is carried out on the basis of slip forms method, which makes it possible to perform a continuous-cyclic process of concreting. The analysis of technological operations for erecting monolith objects has shown that MSRS is to provide concrete shaping, its consolidation, reinforcement placement and anchoring. Block diagram of the system designed for erecting monolith tower-type objects with variable cross-section is presented in fig.1. Its base is a self-moving platform with the forms equipped with mechanisms for changing panels position. The system comprises a concreting robot, which ensures concrete placement against the forms and its consolidation. To mechanize steels placement the system is provided with two robots one of which is responsible for placing and anchoring vertical reinforcement being fed from the handling-storage device and the second one provides placement of the horizontal reinforcement, which is fed by a special device. The analysis of distinctive features of MSRS control and the study of its properties as a multi-measured object tell us that it is obvious to use a two-stage system of adaptive control. Each robot has its own control system performing tactical and executive problems of control. The robotic system comprises a data-measuring system, which monitors the platform and forms position, concrete and reinforcement placing and its data are used for the purpose of control. Planning of technological operations sequence and synchronization of the equipment operation are carried out by the upper level control system. The mechatronic system provides automatic lifting the robotic system, automatic changing the forms radius during the process of lifting and also correction of the platform position. The robotic system control provides synchronized operation of the platform lifting and adjusting mechanisms taking MSRS is a multimeasuring controlled object the states of which at any period of time can be described by the system of equations

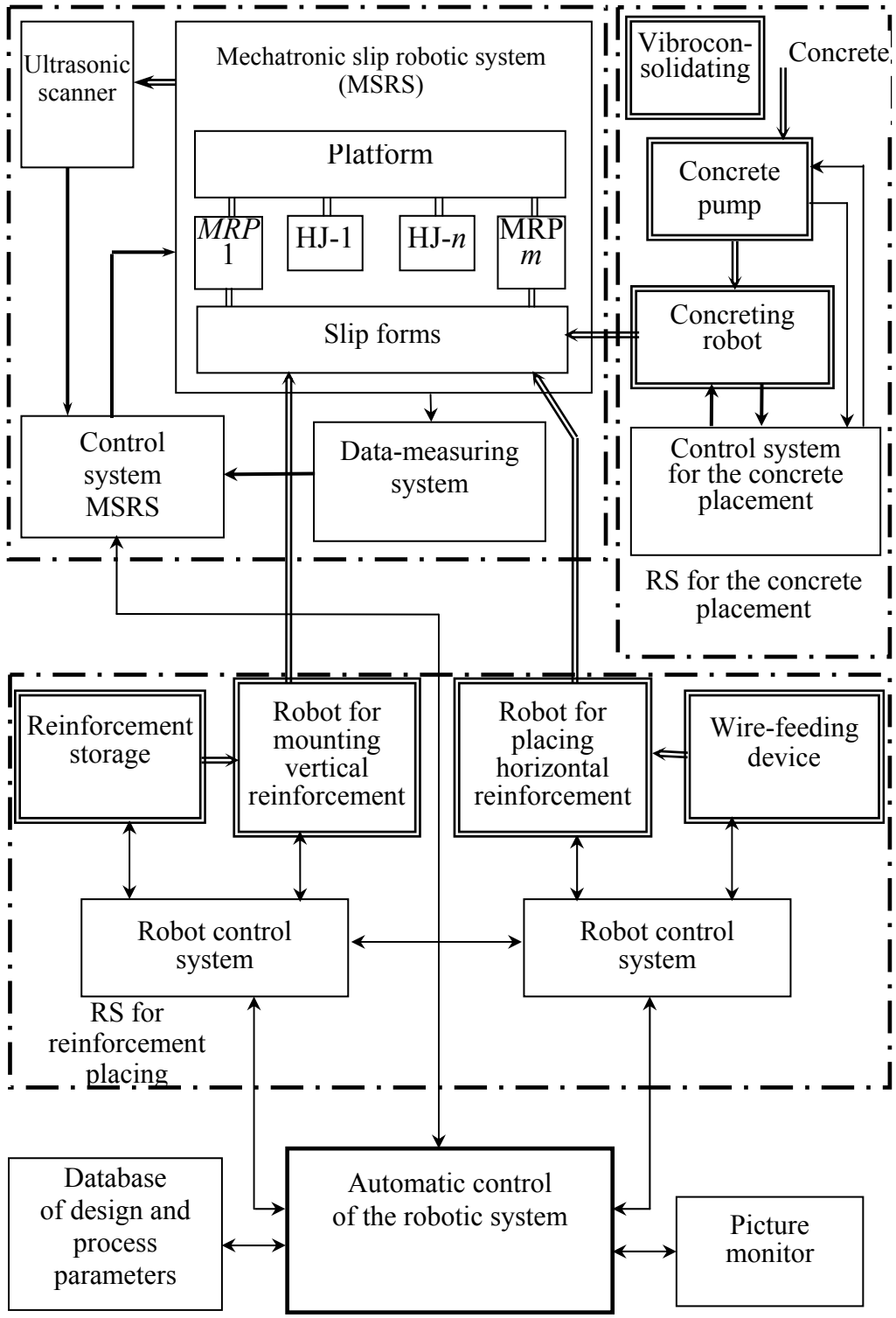

Fig. 1

$$\begin{cases} \overline{U}_{hj} = \left[U_{hj}^{(1)}, U_{hj}^{(2)}, \ldots U_{hj}^{(m)}\right]; \\ \overline{U}_{rm} = \left[U_{rm}^{(1)}, U_{rm}^{(2)}, \ldots U_{rm}^{(n)}\right]; \\ \overline{Y}_{ms} = \left[x_n, y_n, z_n, R_o, \text{б}_n, \beta_n, \text{и}_n\right]; \\ \overline{F}_1 = \left[F_w, F_s\right],\ \overline{F}_2 = \left[Q_н, F_{mp}, F_{сц}, F_{тм}, F_y\right], \end{cases}$$

where $\overline{U}_{hj}$, $\overline{U}_{rm}$ are the vectors of control actions directed to the hoisting jacks and the mechanisms of radial displacement (MRP); $\overline{Y}_{ms}$ is the vector of the output parameters of the MSRS state; $\overline{F}_1$ and

$\overline{F}_2$ are the vectors of disturbing influences acting on the erected construction and the mechatronic system.

The system state at any moment is determined by the coordinates x_p , y_p , z_p of the center position in the system of coordinates of the erected object $X_oY_oZ_o$, by the forms radius R_o, by the angle of the platform inclination α_p, by the direction of the inclination vector β_p and by the platform turning (twisting) angle ψ_p round the vertical axis. For the structures of conical shape the relation between radius R_o and the object height has the form of

$$R_o = R_o^* - (h \cdot \mathrm{tg}\varphi_o)$$

where R_o^* is the radius of the structures at zero mark.

Two groups of quantities are considered in MSRS as control actions. One of them is intended to control hoisting jacks ($U_{hj}^{(i)}$) and the other one – mechanisms of radial displacement ($U_{rm}^{(j)}$). Between these control actions there is a relationship ensuring synchronization of the both groups of mechanism operation.

The process of the system operation is accompanied by influencing on it several kinds of disturbing influences. The first group comprises influences leading to deformation of the erected structure and displacement of the platform with the forms. They cover influence F_s connected with the structure sun-heating and influence F_w caused by the wind load. Due to the temperature difference $\Delta\tau = \tau_s - \tau_c$ of the sunny and shady sides there occurs deformation of the structure and its deviation from the designed axis. The deviation quantity δ_s is the function of the height h, the object diameter D, the walls width b, and the period of heating t_s: $\delta_s = f_s(\Delta\tau, h, D, b, t_s)$. In order to evaluate the influence of the object temperature gradient on the MSRS operation we have introduced the coefficient of deformation, which is calculated by the formula: $k_d^{(s)} = h \cdot \varepsilon_s / (16\pi \cdot R_o)$. The platform deviations connected with temperature heating will be

$$\Delta x_s = 0{,}5 k_s^{(h)} \cdot h \cdot \Delta\phi \cdot \cos и_s;$$

$$\Delta y_т = 0{,}5 k_s^{(h)} h \cdot Дф \sin и_m;$$

$$\Delta z_s = k_s^{(h)} \cdot R_o \cdot \Delta\tau;\ \Delta\alpha_s = k_s^{(\varphi)} \cdot \Delta\tau.$$

As a result of the wind load there occurs inclination of the structure by the angle of α_w and deviation of the MSRS platform center from the vertical. The deviation parameters can be evaluated by the formulae:

$$\Delta x_w = k_w^{(h)} \cdot F_w \cdot \cos\theta_w;$$

$$\Delta y_w = k_w^{(h)} \cdot F_w \cdot \sin\theta_w,$$

where $k_w^{(h)}$ and $k_w^{(\varphi)}$ are the coefficients determined by the structure shape and its rigidity; F_w and α_w are the quantity and direction of the wind load.

The second groups of the disturbing influences constitute those applied to hoisting jacks and mechanisms of radial displacement. During the system operation hoisting jacks are under action of static and dynamic loads created by the weight of the platform, forms, equipment and materials: $Q_\Sigma = \sum Q_i$ and also under the influence of friction forces F_{fr} and cohesive forces F_c of panels with concrete.

The movement of the system being under control actions ($\overline{U}_{hj}, \overline{U}_{rm}$) and disturbing influences ($\overline{F}_1, \overline{F}_2$) is described by the equation:

$$\overline{Y}(t) = A(s) \cdot U_{hj}(t) + B(s) \cdot \overline{U}_{rm}(t) + H_1(s) \cdot \overline{F}_1(t) + H_2(s) \cdot \overline{F}_2(t),$$

where $A(s), B(s)$ is a matrix of particular transfer functions which characterize the dynamics of hoisting and adjusting units; $H_1(s)$ and $H_2(s)$ are matrices of transfer functions in terms of disturbing influences.

3. FORMATION-CONTROL SYSTEM

The solution of the problems of MSRS control is connected with control of the parameters related with the system state and the environment conditions. To control the system lifting it is necessary to obtain data about the platform with forms position, levels of hoisting jacks and radial position of the forms panels. Implementation of the adaptive control laws is connected with forces control in hoisting jacks, wind and temperature loads on the object.

Checking the vertical position of the erected object and the platform position is carried out with laser devices equipped with photomeasuring panels. The laser device consists of two laser set-point devices for the vertical axis and two photoreceiving panels with modules for reading-out and processing data. Location of the laser beam center on the

photoreceiving matrix is determined by the way of photopanels scanning. And the coordinates of the beam center are calculated from the formulae:

$$x_{pr} = 0{,}5\left[\begin{array}{l}\left(8\left(d_i^{(x)} - 1\right) + b_i^{(x)}\right) + \\ \left(8\left(d_l^{(x)} - 1\right) + b_l^{(x)}\right) - N_{pr}\end{array}\right];$$

$$y_{pr} = 0{,}5\left[\begin{array}{l}\left(8\left(d_i^{(y)} - 1\right) + b_i^{(y)}\right) + \\ \left(8\left(d_l^{(y)} - 1\right) + b_l^{(y)}\right) - N_{pr}\end{array}\right],$$

where $d_i^{(xx}$, $d_i^{(yy}$, $d_l^{(xx}$, $d_l^{(yy}$ are initial and last active bytes when scanning along the axes *X* and *Y*; $b_i^{(xx}$, $b_i^{(yy}$, $b_l^{(xx}$, $b_l^{(yy}$ are initial and last bytes corresponding; d_i , d_l ; N_{pr} is the number of digits)in bits) on the photopanel.

On the basis of the beam location coordinates on the photoreceiving panels we determine the position of the platform center:

$$x_{pl} = x_p^{(oo} = 0{,}5\left(x_{pr}^{(1)} + x_{pr}^{(2)}\right) \cdot \cos\psi_p ,$$
$$y_{pl} = y_p^{(oo} = 0{,}5\left(y_{pr}^{(1)} + y_{pr}^{(2)}\right) \cdot \sin\psi_p ,$$

where ψ_p is the twist angle of the platform relative to Z_o axis.

On the basis of the obtained average values of the platform deviation from the designed axis we calculate modulus and the direction of displacement:

$$\delta_{pl} = \left[\left(x_{pl}\right)^2 + \left(y_{pl}\right)^2\right]^{1/2};$$

$$\beta_d = \arccos\left(\frac{x_{pl}}{Д_{pl}}\right) = \operatorname{arctg}\frac{y_{pr}^{(1)} + y_{pr}^{(2)}}{x_{pr}^{(1)} + x_{pr}^{(2)}}.$$

The data received from the photopanels make it also possible to determine the twist angle of the platform with the forms

$$\psi_p = \operatorname{arctg}\left[\left(y_{pr}^{(1)} - y_{pr}^{(2)}\right) / l_{pr}\right],$$

where l_{pr} is the distance between photoreceiving matrices.

The platform deviation is closely connected with disturbance of its horizontal position therefore a hydrostatic leveling device has been introduced into the system. It permits checking the platform deformations and the swivel angle and also deviations of some jacks relative to others. Using level detector readings $\Delta z_{ld}^{(i)}$ we determine upper and lower marks of the platform hoisting jacks position

$$\Delta z_{hj}^{(\max)} = \max\left(\Delta z_{ld}^{(i)}\right); \Delta z_{hj}^{(\min)} = \min\left(\Delta z_{ld}^{(i)}\right) \rightarrow$$
$$i = 1, 2, ..., n$$

and calculate the platform swivel angle and the direction of the swivel angle vector:

$$\alpha_p = \operatorname{arctg}\left(\frac{\Delta z_{ld}^{(\max)} - \Delta z_{ld}^{(\min)}}{4R_{hj}}\right),$$

$$\beta_p = \frac{2\pi}{n}\left[i\left[\max\left(\Delta z_{ld}^{(i)}\right)\right] - 1\right].$$

The data about the jacks' deviation $\Delta z_{hj}^{(i)}$ from the horizontal plane are used to synchronize movements of the hoisting jacks. To provide the platform correcting inclination hoisting jacks' speeds are set according to the required swivel angle α_p^*:

$$v_{hj}^{(i)} = v_p\left[1 + R_{hj} \cdot \sin\alpha_p^* \cdot \cos\left(\frac{2\pi}{n}(i-1) - \beta_p\right)\right],$$

where v_p is the average speed of the platform hoisting.

4. PLANNING OF THE MECHATRONIC SYSTEM MOVEMENT

Planning of the MSRS movement may be considered one of the main control problems, which includes building of the motion path and formation on its basis the control laws for hoisting and adjusting mechanisms. When the platform is in the design position the system displacement is carried out without any correction and described by the algebraic equation

$$z_{pl}^{(w/c)}(t) = \sum_{i=1}^{k-1} h_{pl}^{(i)} + \int_0^t v_{pl}^{(k)} dt,$$

where $h_{pl}^{(i)}$ is the quantity of lifting on the *i*-th step; $v_{pl}^{(k)}$ is the speed of hoisting on the *k*-th step; *k* is the current step of hoisting of the trajectory section under consideration. MRP movement is carried out proportionally to the system lifting and the radius of arrangement of the forms panels changes according to the equation $r_{rm}^{(k)}(t) = \sum_{i=1}^{k-1} r_{rm}^{(i)} + K_\varphi \int_0^t v_{rm}^{(k)} dt$, $r_{rm}^{(j)}(t) = r_{rm}^{(w/c)}(t)$, $(j = 1,2,...,m)$,

where $r_{rm}^{(i)}$ is the radius change for the *i*-th step; $r_{rm}^{(j)}(t)$ is the forms' panels displacement by the *j*-

th MRP; $K_\varphi = (\mathrm{tg}\varphi_o)^{-1}$ is the coefficient of proportionality determined by the object taper.

During the process of the system lifting there may be deviations from its design position and their compensation requires building correcting trajectories. Taking into account the requirement of monotonicity and smooth transitional trajectory and also limitations on its curvature, which can be defined by the forms' panels taper, we suggest to divide the correcting trajectory into two sections (fig. 2).

The first change (*AD*) deals with gradual change of the forms' swivel angle in order to reduce deviations. In the first part of the section (*AB*) there is an increase of the platform deviation from the design axis and it reaches its maximal value $\delta_p^{(\max)}$ in point *B*. While approaching the design axis it goes to the second section (*ED*) and it is during this part that the platform is gradually leveled. After the correction has been completed (*E*) the platform center is to take the design position and the platform itself – horizontal position.

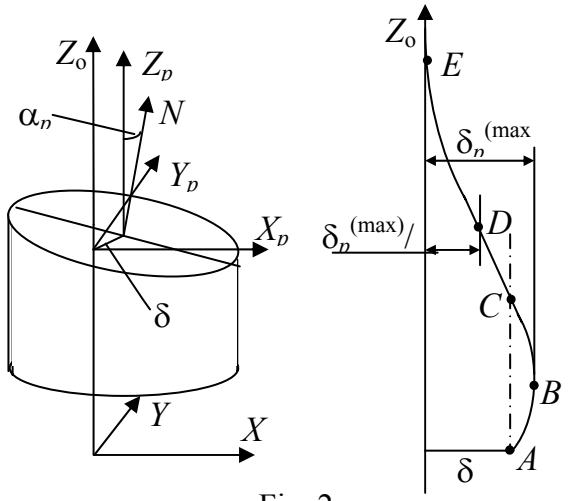

Fig. 2

Applying the results of the investigations we suggest to approximate the first part of the trajectory by the parabolic function

$$\delta_1(l) = a_2 l^2 + a_1 l + a_0$$

the coefficients of which are determined from the initial conditions:

$$\delta_1(0) = a_0 = \delta_p;\ \dot{\delta}_1(0) = a_1 = \alpha_p^*;$$

$$\ddot{\delta}_1(0) = a_2 = -\gamma/2$$

The second trajectory section (*DE*) is to provide smooth approach to the design axis with simultaneous platform leveling in point *E*.

These requirement are satisfied by exponential dependency

$$\delta_2(l) = C_{21} e^{\lambda_{21}(l-l_s)} + C_{22} e^{\lambda_{22}(l-l_s)},$$

where l_s is the path of conjugation of two trajectory sections (point *D*).

Applying approximating dependencies we present the MSRS movement trajectory while correcting the platform position in the form of

$$\delta(l) = \begin{cases} a_{12} l^2 + a_{11} l + a_0 & \rightarrow\ l < l_s \\ C_{21} e^{\lambda_{21}(l-l_s)} + C_{22} e^{\lambda_{22}(l-l_s)} & \rightarrow\ l \geq l_s \end{cases}$$

The trajectory points coordinates at the end of the next lifting step *k* are connected with the equation $\delta(l)$ by the relationships:

$$x_p^{(k)} = \delta(l_k)\cos\beta_p;\ y_p^{(k)} = \delta(l_k)\sin\beta_p,$$

$$z_p^{(k)} = z_p^{(A)} + l_k,$$

where $l_k = k \cdot h_s$ is the travel from the initial correction; h_s is the lifting step.

The control influences formation is carried out on the basis of planning algorithms subject to adaptation to heat and wind influences on the erected object. The points coordinates of the planned trajectory at each lifting step are corrected by the amount of existing thermal and wind deviations. Control influences for hoisting mechanisms are generated with account of the platform slope compensation because of thermal and wind deformations. The direction of the slope is determined by the direction of external influences on the object.

5. CONCLUSION

The presented paper has been prepared on the basis of the authors' research work, which was carried out during the development of the problems dealing with automation and robotization of monolith construction. The presented principles of the mechatronic slip robotic system creation can be used while developing the projects for robotization of construction of chimneys, television and observation towers, water-cooling towers and other objects of monolith concrete. Data-measuring information described in the given article is put into the basis of the developed by the automatic system for collecting and processing measuring data for MSRS which contains interface supplying all necessary data about the system condition and graphical display of its position. Computer simulation of MSRS lifting has demonstrated efficiency of the suggested procedure of movements planning and control influences development and the described approaches can serve as the foundation for developing the system control algorithms.

Developing a Convenient Balance Beam for Unknown Loads

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Abstract: Balance beam, a controller that is built adopting the gyro effect, can freely control the attitude of an unstructured object by means of the position controlling of an inner gimbal. However in the former research, the weight (inertia) of a load should be known to issue a proper command for the gimbal, which makes it hard to operate the balance beam in field applications because the load can be changed frequently and, moreover, the inertia of the same load could be different according to how the load is held. Therefore an accident could be caused by the operation with an improper gimbal command.

One of the possible approaches to solve the problem is to give a balance beam controller an ability to detect the inertia of a load so that it can limit the velocity of the load ordered by a user. In this paper, we designed a controller that can estimate the inertia of the load based on the result we did before; the fact that when there is smaller inertia of load, the larger amount of the restoration displacement occurs. Thus, the load could be identified by issuing a predefined command to measure the amount of the restoration displacement, which makes us able to construct the controller that can limit the angular velocity of the load by planning the motion. Experimental results show the performance of the controller with some loads.

Keywords: gyro effect, balance beam controller, construction equipment, load estimation, gimbal

1. INTRODUCTION

In this paper, we designed the balance beam controller which can control unknown load using the CMG (control moment gyro) subsystem. Usually, gyro consists of a wheel spinning at high speed. It has a tendency to maintain its spin axis in a fixed direction in space. A torque exerted about any axis other than the spin axis produces a rotation about the axis that is orthogonal to the applied-torque axis[1][2]. We designed and implemented CGM subsystem for balance beam which has a rotating wheel at high speed and outer gimbal connected to the motor. As the attitude of the outer gimbal changes, rotation force occurs about the vertical axis if the balance beam is mounted on the object in air. We use the torque produced to control the attitude of the control object.

The CMG characteristics are addressed in a few researches such as the stabilizer for gondola and aircraft. Hiroshi KANKI and et al.[3] developed CMG active vibration control device for gondola to reduce random wind force. And, Ahmed and et al.[4] studied on the gyro pendulum to eliminate the effects of mass imbalance in rotating bodies. Attitude control of spacecraft was addressed by Li and et al.[5]. Except for KANKI, all these studies have not addressed on an attitude control but on a stabilization of the spacecraft.

In our previous study, we expanded the application area of CMG subsystem from attitude control of the objects only to its stabilization in space. Furthermore, we designed an attitude controller of gimbal with gyro actuator that used wireless communication for actual application in field. However, in the unknown load inertia case, it is not easy even for skilled workers to operate a balance beam. That is caused by the difficulty in estimating the load inertia. If the excessive gimbal operation takes place with wrong estimations, accidents are likely to happen.

In this paper, we attached angular velocity sensor to gyro actuator to stabilize the attitude control of balance beam. Next, we estimated the inertia of load

using the output of angular velocity sensor and simple manipulation. Using the developed controller that can control the angular velocity of the balance beam, we make it easy to drive and strengthen the stabilization of the previous controller.

2. BALANCE BEAM

In this chapter, we will explain what the gyro effect is and how to build the balance beam. We will also briefly introduce the mathematical methods of the balance beam.

2.1 Gyro effect

In Figure 1, L_x represents angular momentum about x-axis, N_y and J_ω stand for torque about y-axis and the inertia of wheel, respectively.

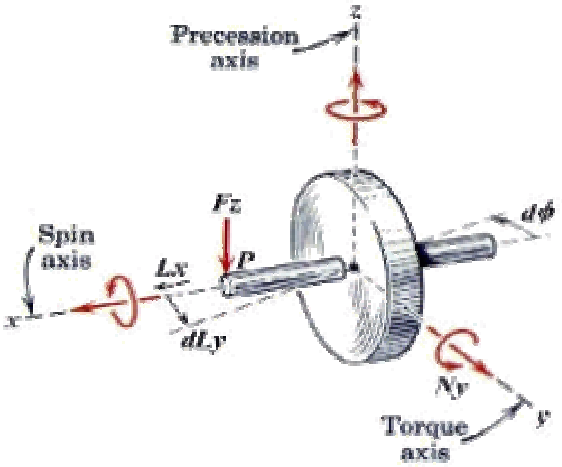


Figure 1. Gyro dynamics

Exerting force at arbitrary point P, we get a torque about y-axis, N_y, as bellow,

$$\frac{dL_y}{dt} = N_y \tag{1}$$

and we get a changed angular momentum

$$L = L_x + dL_y \tag{2}$$

Since a change of angular momentum, dL_y, is smaller than L_x

$$d\phi = \frac{dL_y}{L_x} \tag{3}$$

Substituting (1) into (3), we get

$$\frac{d\phi}{dt} = \frac{N_y}{L_x} \tag{4}$$

From this equation, one can see that rotational motion about the vertical axis, z, could be obtained by applying torque about y-axis.[1][2]

The other, rotational motion torque about horizontal axis, y, is obtained by gimbal motor. At the same time, ϕ, the rotation of load obtained by vertical axis, z.

2.2. CMG subsystem

In this section, the structure of the CMG subsystem, modeling of the system, the controller for the gimbal motor and the wheel motor are explained.

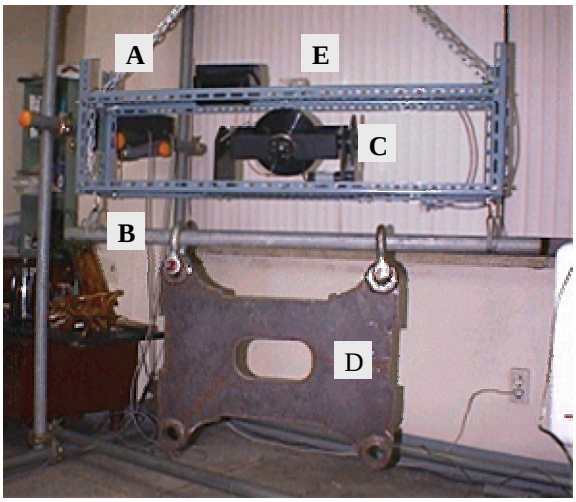


Figure 2. A balance beam system and load

The fabricated CMG subsystem in laboratory scale is shown in Figure 2, and enlarged gyro actuator is shown in Figure 3.

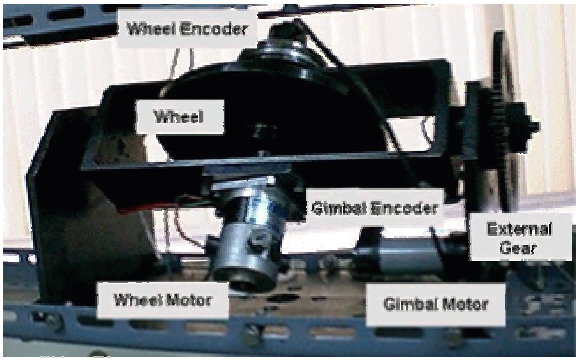


Figure 3. The structure of CMG subsystem

As shown in Figure 2 and 3, the control system consists of a wheel spinning by a motor, inner gimbal supporting the wheel and the wheel motor that is fixed to inner gimbal, and outer gimbal supporting the inner gimbal and gimbal motor that is fixed to outer gimbal. Inner gimbal position can be controlled by the gimbal motor. As shown in Fugure 2, CMG subsystem is suspended from a structure through a swivel hook that has little friction.

The structure (B) to be hung the load (D) is shown

in Figure 2, and the details of CMG subsystem (C) is shown in Figure 3. The CMG subsystem consists of a high speed wheel and a gimbal that can control the attitude of the balance beam by means of adjusting the wheel rotation axis.

The piezoelectric vibrating gyroscope sensor is shown in Figure 2 (E). It can measure the load inertia using measurements of rotation velocities of the load. Also, a motor and an encoder are attached to both the axis of the wheel and the axis of gimbal.

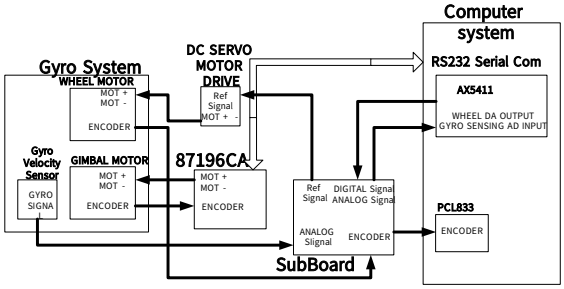


Figure 4. System block diagram

Subsystem block diagram in Figure 2 is shown in Figure 4. The control system consists of a 32-bit computer, Pentium-133MHz, an AX5411 A/D-D/A converter by Axiom Co., PLC833 3-axis quadrature encoder by Adventech, and an amplifier working in torque mode which ha been built with power driver module, 12A8E, 5A5 by Advanced Motion Control. One encoder is used to measure the angular velocity of wheel, and the other encoder is used to measure inner gimbal position and velocity (500pulse through 18:1 gear reduction, and 4:1 external gear). Because the encoder body which measures angular velocity of the wheel can not be fixed firmly to wheel shaft, some noise is made. We solved this problem using second order butterworth filter in CMG control program. The wheel motor is 60[W] DC motor by Tamagawa seiki and gimbal motor is 15[W] DC motor by Maxon.

Also, we attached piezoelectric vibrating gyroscope sensor for sensing the angular velocity of load. 12-bits digital value that is changed by AX5411 A/D-D/A converter installed in computer could be measured by that sensor. The attitude of gimbal motor is controlled by means of the LMD18200. Control Board, 87C196 that is developed in our laboratory can control the attidude of load.

The specifications of the major parts organization of the system are listed in Table 1. The inertia of the balance beam is obtained by assumption that the frame and CMG are regarded as a rectangular parallelepiped of which mass has been distributed evenly.

2.3 CMG subsystem modeling

We derive the modeling of CMG subsystem from assumptions that gimbal is lighter than wheel (weight of the gimbal can be regarded as load), a viscous-friction of swivel hook and bearing is very small, and motor inductance is negligible.

Table 1. The parameters of the system

Device	Specification
Wheel Motor	Tamagawa TRE PMDC 60[W], 1000p/r Encoder
Gimbal Motor	Maxon Amax110857 DC 15[W], 500p/r Encoder, 72:1 Reduction
Wheel mass /diameter	2.69[kg], 199.9[mm] diameter
CMG subsystem mass	24.55[kg]
Frame mass and dimension	9.3[kg], 789x200x200[mm]
Balance beam inertia	1.86[kgm^2]
Main Controller	87c196CA Control Board

The transfer function from the voltage applied to the angle of the gimbal motor is

$$G_1(s) = \frac{\theta_{gc}(s)}{v_a(s)} = \frac{k_m}{s(\tau_m s + 1)}$$
$$k_m = \frac{k_1}{(k_k k_b + f_m R_a)} \qquad (5)$$
$$\tau_m = \frac{(J_{gr} + J_c) R_a}{(k_k k_b + f_m R_a)}$$

Where, k_b, k_t, and τ_m are back-emf constant, torque constant, and time constant, respectively [8]. R_a stands for armature resistance, J_{gr} represents rotor inertia of gimbal motor, J_c for the wheel inertia of circular disk turning about its radial axis.

Then, we assume that the gimbal is lighter than wheel. We considered the case which the load is attached to the gyro actuator.

The relationship between the attitude of the inner gimbal, θ_{gc}, and rotation about vertical axis, ϕ, is

$$(J_{gr} + J_c)\frac{d^2\theta_{gc}}{dt^2} + f_m \frac{d\theta_{gc}}{dt} = J_w \omega_w \frac{d\phi}{dt} - J_l \frac{d^2\phi}{dt^2}$$
$$J_w = M_w \frac{r^2}{2} \qquad (6)$$
$$J_l = M_l \frac{(a^2 + b^2)}{12}$$
$$J_c = M_w \frac{r^2}{4} + M_w \frac{h^2}{12}$$

Where, M_w and M_l are mass of wheel and mass of load, respectively. r, h, a and b represent radius of wheel, thickness of wheel, length of load, and width of load, respectively. J_w means wheel inertia about spin axis. Then, transfer function G_2(s) is

$$G_2(s) = \frac{\phi(s)}{\theta_{gc}(s)} = -\frac{(J_{gr} + J_c)s + f_m}{J_l s - J_w \omega_w} \quad (7)$$

Transfer function of the overall system G(s) is obtained from (5) and (7) as following:

$$\begin{aligned} G(s) &= -G_1(s)G_2(s) \\ &= \frac{1}{s}\frac{(J_{gr} + J_c)k_m s + k_m f_m}{J_l \tau_m s^2 + (J_l s - J_w \omega_w \tau_m)s - J_w \omega_w} \\ &= \frac{1}{s}\frac{b_1 s + b_0}{s^2 + a_1 s - a_0} \end{aligned} \quad (8)$$

Where, a_0, a_1, b_0 , b_1 are determined by the motor parameters and the shape and angular velocity of the wheel. Notice that a_1 depends on the load inertia, and transfer function has an unstable pole.

3. BALANCE BEAM CONTROLLER

In this chapter, we will explain what the restoration of a gimbal is and how to use it to figure out the inertia of an unknown load. Furthermore, we will present a controller incorporating the restoration that can control the angular velocity of an unknown load by adjusting the proper gimbal command.

3.1 Restoration angle of gimbal

When we issue the gimbal motion command, the load rotates according to the amount of the command. However, if we cut the power of the gimbal, which initiates the stabilizing mode of the balance beam, it goes backward to stop the load. At this time we define the restoration angle as the difference between the issued gimbal angle and the angle when the load stops.

Here we investigate the relationship between the restoration angle and the load.

The loads, iron plate shown in Figure 2, considered here are summarized in Table 2, where the inertia values in the parentheses are the values including the inertia of the balance beam.

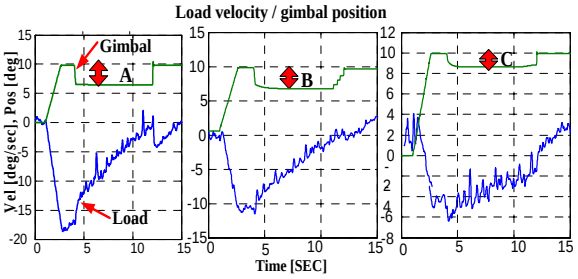
Table 2. Weight and inertia of load

Load	Weight [kg]	Inertia [kgm^2]
No load	0	0.00 (1.86)
Load 1	55	0.74 (2.70)
Load 2	55	2.12 (4.12)

Actually, loads are same, but the hanging direction is different; one is crosswise and the other is lengthwise. The motions of different loads to the gimbal command, 10 degrees, are depicted in Figure 5.

Note that the line marked as load represents the angular velocity of the load measured using the rate gyro sensor built in our lab [6]. The signal seems too noisy since the balance beam was chattering caused by the wheel noise. Actually, the sensor information is not involved in the controller, but it is just a monitoring signal to check the load angular velocity in this study.

In Figure 5, we can see the restoration angles (A, B, C) for different loads, which are getting smaller as the load increasing. Note that the figure (c) is enlarged for the purpose of the comparison. The detailed results are summarized in Table 3.



(a): No Load (b): Load 1 (c) Load 2

Fig. 5 The load angular velocity and gimbal trajectory

Table 3. Gimbal restoration angle for loads

Load	Gimbal command	Restoration angle
No Load	10°	3.27
Load 1		2.10
Load 2		1.58

The results for the different gimbal commands are not listed here since angles which are too small cannot give distinct restoration angle, whereas a too large one would make the load turn too much; exceeding testing angles. More experiments with various kinds of loads are needed to obtain the more precise characteristics line, but we present 3 points (small circles in the Figure 6) in this experiment.

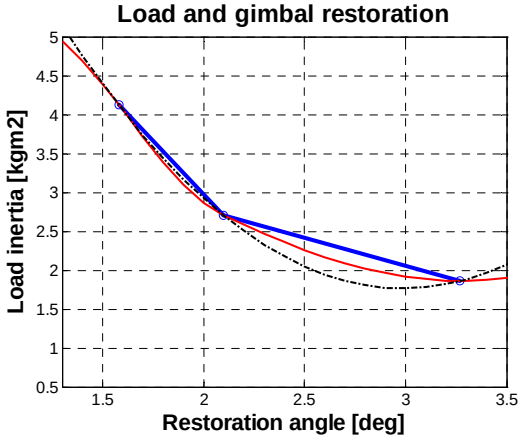


Figure 6. Load inertia and gimbal restoration angle

It is possible to figure out the load if we measure the restoration angle by issuing test command before the actual command. To do this, we have to find the relationship function between load and restoration angle by the second order fitting equation to the results in Figure 6 (dashed line), as follows. This can be obtained using the Matlab function 'fit' with the fitting option 'pchipinterp' as shown in the figure (light solid line).

$$y = ax^2 + bx + c$$
$$a = 1.1910,\ b = -7.1137,\ c = 12.3864 \quad (9)$$

The algorithm to implement this procedure, unknown load estimation, is as follows.

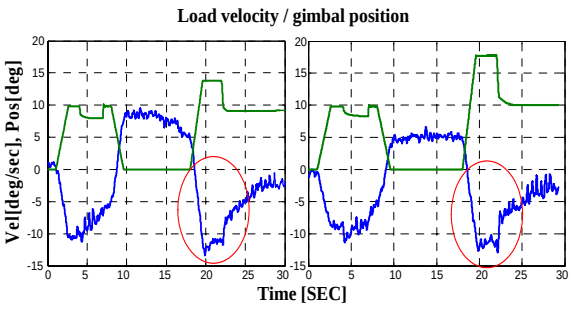
STEP 1 : Detect peak value of the gimbal with given gimbal command.
STEP 2 : Enter stabilizing mode by turning off the power of gimbal.
STEP 3 : Detect level value of the gimbal when load stops.
STEP 4 : Calculate restoration angle by subtracting the peak value with the level value.
STEP 5 : Find the inertia of the unknown load from the fitting equation.

3.2 Load motion to gimbal command

In the previous section, we could estimate the inertia of the unknown load. Now it is necessary to decide proper gimbal command angle for the load. To do this, figuring out the relationship between load and gimbal command angle is needed, which requires extensive experiment for many known loads at specific angular velocity of the loads, 12.5 [deg/sec]. The results are shown in Table 4 and some are illustrated in Figure 7.

Table 4. Gimbal restoration angle for loads

Load	Inertia	Restoration angle	Gimbal command
Load 1	1.86	3.27	11
Load 2	2.70	2.10	14
Load 3	4.12	1.58	18



(a): Load 2 (b): Load 3

Figure 7. The load angular velocity and gimbal trajectory

The circled parts, in the figure, stand for the angular velocity of the load that we have to notice whereas the beginning parts are for the operation to obtain the restoration angles. The details of the gimbal operation are as following:

Operation 1: position command, 10 degree, at 1 second.
Operation 2: motor power off at 4 second.
Operation 3: motor power on at 7 second.
Operation 4: position command, 0 degree, at 8 second.
Operation 5: position command, desired degree, at 18 second.
Operation 6: motor power off at 22 second.

The relationship between load and gimbal command angle is as in Figure 8. From this figure, we can find the relationship function between load and gimbal command angle by fitting an equation to the result. This can be obtained using the method used for the Figure 6.

$$y = ax^2 + bx + c$$
$$a = -0.3339,\ b = 5.0938,\ c = 2.6805 \quad (10)$$

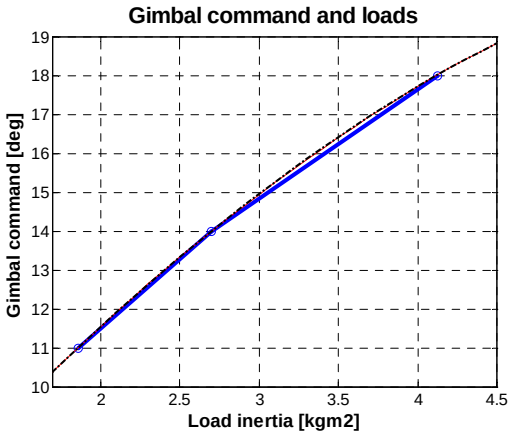


Figure 8. Gimbal command and loads

3.3 Load control

Following the procedures listed above, we demonstrate velocity control of an unknown load using the balance beam. We made unknown load by putting two stuffs on the frame hanging the load 1 shown in Table 2, which has inertia between load 1 and load 2 but it is not necessary to measure it because we have to deal with the unknown load. The target velocity is 12.5 [deg/sec].

We could have estimated the load to be 5.27 since we have the restoration angle 1.27 (A in the Figure 9), which came from the fitting equation (9) in Section 3.1 and is bigger than we expected. However, it seems reasonable because the gimbal command angle for this load, 20.25 in degree, is bigger than the angle of the load 3, 18.0 in degree.

The gimbal command angle was obtained from

the fitting equation (10) in Section 3.2, which had been modified by the controller based on load had estimated.

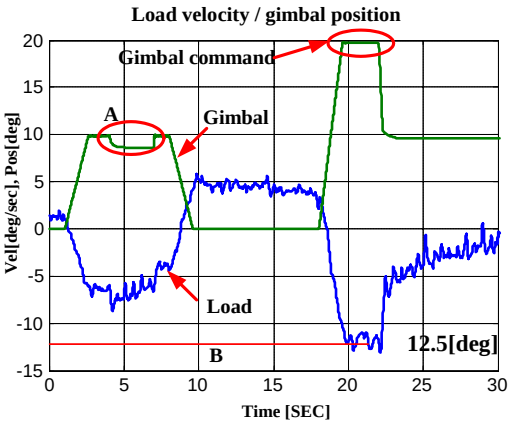


Figure 9. Angular velocity of unknown load and gimbal trajectory

In the figure, 'Load' stands for the angular velocity of the unknown load monitored by the gyro sensor, 'Gimbal' represents the angle of the gimbal. Note that the velocity of the unknown load is about 12.5 [deg/sec] as expected (B in the figure).

4. CONCLUSION

In this work, we designed a balance beam controller that can estimate the inertial of unknown load and control the angular velocity of it.

Unknown load could be estimated by investigating the characteristics of the restoration angle of the balance beam. We defined the fitting equation to estimate the load with the restoration angle measured. We also defined another fitting equation which can decide gimbal command angle by the estimated load. Finally, we could be able to implement the balance beam which can control the velocity of the unknown loads without an angular velocity sensor.

Thru an experiment we were able to show that the controller we developed is very convenient in handling construction work.

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Remote management of LonWorks based control system for air conditioner

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Abstract: In this paper, we describe implementation and test result for a LonWorks based control system in which air conditioner is handled by LonWorks node. The LonWorks based control system for handling air conditioner remotely is integration of control nodes because LonWorks is a communication protocol which is adopted as a standard protocol in building automation systems. For the remote management of distributed control system using Lonworks, we develop protocol converter based on SoC, where there is a Neuron Chip and Embedded Linux is running. The experiment result show that protocol converter using Embedded Linux is a flexible and effective way to build a distributed control system. And the LonWorks based control system for air conditioner is useful way to give interoperability.

Keywords: Remote monitoring and control, Distributed control, system, Embedded Linux, Protocol converter, LonWorks network

1. Introduction

In this paper, we describe implementation and test results for a LonWorks based control system in which air conditioner is handled by LonWorks node. The developed LonWorks control system consists of 6 nodes such a thermometer, 7-segment, pump controller, luxmeter, LEDs, and air conditioner. Originally, each manufacturer built their own system and provided all the intelligent devices within the system. Therefore, it has been historically difficult to interconnect digital controllers from different manufactures. And standardization requires an open control network. A market standard for communication would allow interoperability that would empower the market to increase in size and efficiency, that brought about the introduction of LonWorks protocol. The advantage of LonWorks based control system for handling air conditioner remotely is integration of control nodes because LonWorks is a communication protocol which is adopted as a standard protocol in building automation systems.[1] Therefore, the interoperability between air conditioners made in different manufacturers is achieved so that it is possible to handle build control system in a unified way.

For the remote management of distributed control system using LonWorks, we develop protocol converter based on SoC, where there is a Neuron Chip and Embedded Linux is running. It is a tendency which uses an Embedded Linux instead of Real-Time operating system and commercial embedded operating system. Linux is utilizes the network environment and therefore requires and appropriate operating system for handling protocol and an advanced development environment. The open source licensing, reliability, and broad hardware support are key reason for use of Embedded Linux in embedded industry. The protocol converter integrates control networks of LonWorks devices to distributed control system through TCP/IP protocol. This implementation is a Web-based monitoring and control. For this purpose, embedded web server porting to Embedded Linux is performed. A Java Applet is designed in which Java socket program and GUI for users are performed. [2,3,4]

3. Development of Protocol Converter

For useful management for control network, a protocol converter is implemented. It consists of two CPUs. One is S3C4530A based on ARM7TDMI core that is used for Embedded Linux and controlling peripherals. The other is a Neuron chip supporting LonWorks. The first part of ARM-based SoC is designed to interface TCP/IP, RS232C and LonWorks protocols. The LonWorks suggested by Echelon is protocol supporting OSI 7-layer. The LonWorks is proper to control and monitor network devices just like LAN. The network data from LonWorks is collected in a Neuron chip embedded in the protocol converter. The data should be transferred to ARM CPU that is a main processor. Therefore, DPRAM of CY7C53150 chip of eth Cypress is also implemented to communicate between the Neuron chip and S3C4530A. And we ported Embedded Linux.[5]

3. LonWorks Control Devices

LonWorks is a communication protocol which is adopted as a standard protocol in building automation systems and a control network using Neuron chip. Neuron chip is a VLSI integrated with microprocessor from MAC layer of this LonTalk protocols until application layer. In this paper we implement node devices of LonWokrs using Neuron chip as distributed control network. The node

controller is developed with Lonworks hardware and interface circuit in order to implement various control objects. Table 1 shows specifications of LonWorks devices. In Fig 1, there is interface circuit handling peripherals with memory-mapped I/O or general purpose I/O. Therefore, the control nodes of Fig 2 are implement by using LonWorks control module while adding interface logics. In LonWorks, lots of transceivers are supported such as twisted pair, power line, and RF, etc. The control node is implemented with twisted pair of FTT-10. The communication rate is 76.8Kbps.

Table 1. Hardware specification of LonWorks devices

CPUs		CY7C53150
Memory	FLASH	32KB
	SRAM	32KB
Peripherals		11 GPIO
		Memory Mapped I/O

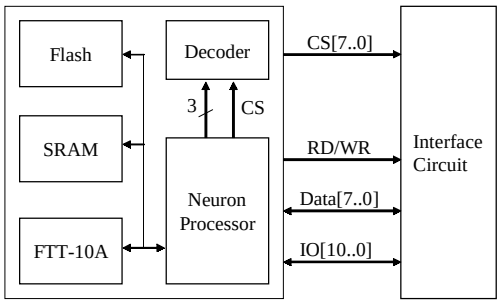

Fig 1. Block diagram of LonWorks devices

Fig 2. shows a devloped control network of LonWorks, in which the control nodes are air conditioner control(AIRC), pump control(PUMP), temperature sensing(TEMP), luminous intensity sensor(LUX), and display nodes such as 7-segment(SEG), and Leds(LED).

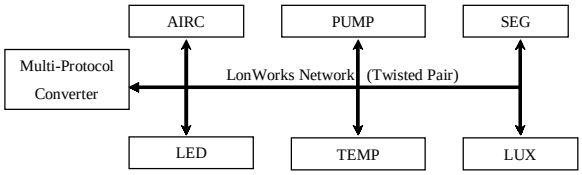

Fig 2. LonWorks network of control devices.

4. Software Structure of LonWorks Network

The program of LonWorks is done with Neuron C based on an event-driven program. The data type of network and I/O port are available. In order to communicate with LonWorks devices in the network, the network variable should be connected to each other and this is done by network binding. Binding is defined as logical connecting variable placed at distributed control nodes so that the communication between nodes is accomplished. In this paper, we use network variables and both variables declared at input and output nodes should be of the same data type.

The binding example is described in Fig 3.

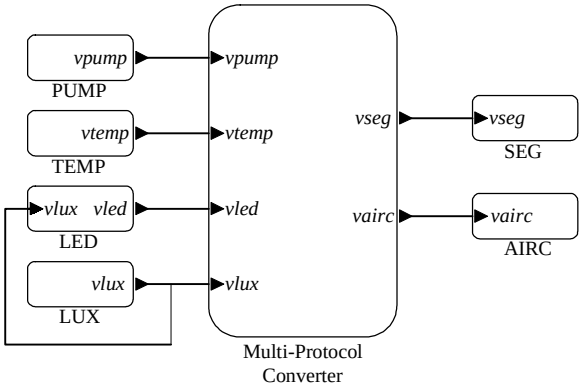

Fig 3. The structure of binding for network variables

The output variables in the protocol converter are defined for segment data and air-conditioner control. The output variable of vairc is a command to control air conditioner such as power on/off, target temperature, and the direction of wind blind. The other output variable of vseg is sued to send segment data to SEG node. The input network variables in protocol converter are vpump, vtemp, vlux, and vled to receive sensing or status data of nodes. The node referred to as TEMP and LUX are designed to measure the temperature and illumination with A/D converter. The data of LUX node is transferred to LED node to display the status, and it is sent to protocol converter.

5. Mechanism of Data Transmission

The commnunication between Java Applet and protocol converter is done through TCP/IP socket programming so that the command from Java Applet is transferred to LonWorks control network device or data gathered from LonWorks control devices is transferred to Java Applet. Therefore, the program in protocol converter is designed to gather data received from each protocol and convert it to socket data to utilize TCP/IP. The software of Server implemented at protocol converter is programmed specifically as Lon_driver.

Lon_driver is used to communicate LonWorks device, however, it is directly handling LonWorks devices but storing data or getting data to/from DPRAM. In Server function module, the decoding of data received form Java Applet through TCP/IP is achieved and the decoded data is sent to appropriate node. The operational order of Server program is as follows:

- creating socket server and waiting for the connection of Java Applet
- creating new thread and starting to communicate with Java Applet through socket when connection from Java Applet
- analyzing the data received from Java Applet and returns with corresponding response

- terminating thread and waiting for the connection of Java Applet again

We examine TCP/IP packet on how to transfer command to LonWorks network. The packet in Server program is defined as Table 2. The data field of addr is to describe the protocol type of control and the termination of the program. The cmd is used for command and the additional command information is included in dataL and dataH. In the case of sending packet, pump, temp, lux and led have the status of each devices.

Table 2. The packet format of TCP/IP

recv packet

'$'	addr	cmd	dataL	dataH	'#'

send packet

'$'	pump	temp	lux	led	'#'

The data transfer between two CPUs is perform in DPRAM with interrupt signal as shown in 4. In order to trigger interrupt signal, intention signal is written at 0x7f2 after writing data such as cmd, addr, dataL and dataH onto DPRAM. Then CY7C53150 chip read DPRAM according to interrupt signal. The received data is sent to the appropriate node through LonTalk protocol.

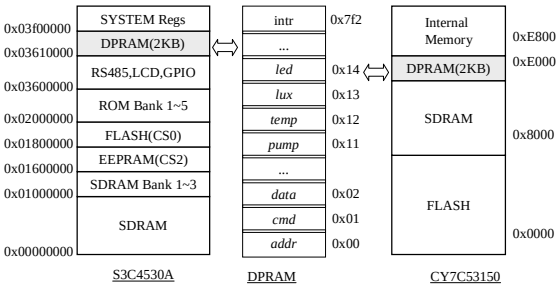

Fig 4. The data transfer mechanism between two CPUs

6. Implementation System

For remote management of LonWorks based control system for air conditioner, we used Java Applet and embedded Web-server on Embedded Linux.

To our knowledge, little architectural work has been done to show the suitability of Embedded Linux for remote management of LonWorks based control system in terms of protocol converter. In the protocol converter, Boa Web Server to be sued for Web service and Network Server for socket communication between Java Applet and Lon Device Server for LonWorks communication are performed. Java Applet is initially placed at the protocol converter and it is uploaded to client after connection Boa Web server from Web browser and it is running in client. The objective of Java Applet is to build GUI and perform socket communication between Java Applet and Network Server running in protocol converter. Fig 6. shows a implemented GUI.[6]

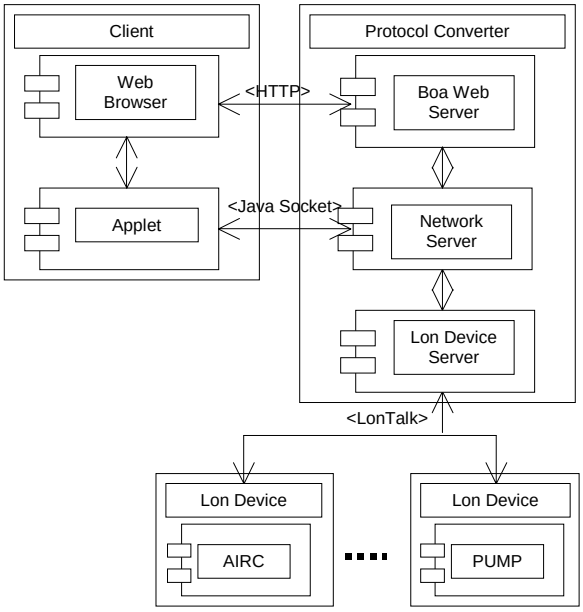

Fig 5. The structure of distributed control system with protocol converter

Fig 6. GUI implemented with the air conditioner in Java Applet

7. Implementation System

In this paper, we designed a remote management of LonWorks based control system for air conditioner. A protocol converter and the LonWorks devices are implemented.

The experiment result shows that protocol converter using Embedded Linux is a flexible and effective way to build a distributed control system. And the LonWorks based control system for air conditioner is useful way to give interoperability

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MIXED REALITY TECHNOLOGY APPLICATIONS IN CONSTRUCTION EQUIPMENT OPERATOR TRAINING

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Abstract: This paper provides information on Mixed Reality (MR), and more specifically Augmented Reality (AR) and their potential applications in heavy construction equipment and operator training. Mixed Reality involves the use of special display and tracking technologies that are capable of seamlessly merging digital (virtual) content into a real environment. Conceptual designs and application scenarios of two AR systems for construction are presented: an AR-based equipment management system (AR EMS) for maintenance, and repair of heavy equipment fleet, and an AR-based operator training system (AR OTS) that trains the novice operators in a real worksite environment populated with virtual materials and instructions.

Keywords: mixed reality, augmented reality, machine operator training, heavy construction equipment management.

1. INTRODUCTION

While construction equipment operators usually develop their skills on the job, it is generally accepted that formal training provides more comprehensive skills. The nature of construction equipment and the materials they may be used to handle makes such training expensive. Research has shown that the key to acquiring the necessary motor skills to control complex systems, such as a backhoe excavator, is hands-on and coached training [3]. Some research has considered the need of such hands-on experience by developing physical training systems. For example, Bernold et al. [2] developed an Internet-based prototype training system for backhoe operators with which the remotely located novice can manipulate a laboratory excavator via a joystick.

Personnel involved in equipment management also monitor equipment condition, maintain and repair equipment components by referring to technical specifications, and generate more information for future access. These individuals often face the problem of not finding the right information in a timely manner. Furthermore, critical information exists on different platforms (e.g., paper-based specification, standalone-computers) characterized by a lack of mobility. This practice makes it difficult to process information at any time and place.

Two innovative AR-based systems to visually merge digital information into the current workspace are conceptually developed for construction equipment operator training and equipment management.

2. MIXED REALITY TECHNOLOGY

2.1 Mixed Reality: general description

Mixed Reality (MR), defined by Milgram et al. [5], is a special class of Virtual Reality-related technologies for creating environments wherein real world and virtual world objects are presented together in a single display. Augmented Reality (AR), a sub-mode of MR, can provide an augmented workspace by inserting content from the virtual space in which we store and interact with digital content into a predominantly physical space where we work. The need for good operator training and for access to large amounts of equipment management information creates conditions making use of AR techniques most promising for engaging construction personnel into augmented workspaces. AR allows a user to work with the real 3D environment while visually receiving additional computer-generated or modeled information about the task at hand. Such displays can enhance the user's perception of the real environment by showing information the user cannot directly acquire unaided.

2.2 Mixed Reality: technological components

Augmented Reality is typically based on four major technological components discussed as follows:

Media representation: AR systems typically use more varied media for presenting the digital content than VR. The identified major classes of media representations from abstract (schematic) to realistic (3D) are text, indicators, platform (tablet and screen), 2D image, 3D wireframe, 3D data, and 3D object. It

is apparent that realistic representations convey more intuitive information that can assist an individual's comprehension thus augmenting the cognitive process and activity. Hybrid representations (e.g., texts + 3D object) can be very useful in situations where different cognitive channels need to be provided.

Input device: An input device is used to manipulate the digital information displayed over the real environment. Most of the input devices used in VR can also be applied in AR systems. A poor input metaphor may create a number of problems for the user. For example, intermediate devices such as joysticks actually place themselves between users and environments, requiring significant cognitive mapping to perform tasks. Aural and haptic input can be integrated to increase input capability of the system.

Display device: The display can be generally classified as visual display, acoustic display, tactile display etc. Head mounted displays (HMDs) were developed for visual rendering, 3D localized sound systems for aural rendering, force feedback devices for haptic rendering, etc. Visual displays are key to AR systems with the other types of displays as possible supplements. The wrong display may burden the user's physical and cognitive processes and reduce usability.

Tracking technology: Position and orientation tracking, are used where the orientation and the position of the user's head or hands, and sometimes eyes are required. Accurate registration—positioning and alignment—of virtual objects in the real environment requires accurate tracking from the user's viewpoint and sensing of the locations of other objects in the environment. The tracking technology must update position and orientation values in real-time as the user may move around in the real environment. Each class of tracker has its own advantages and disadvantages. For detailed comparison of tracking technologies, readers are referred to [4]. Tracking systems that might meet the stringent requirements of AR for construction will probably be hybrid systems, such as a combination of inertial and optical technologies [1] because hybrid systems may compensate for the shortcomings of a single technology by using multiple sensor types to produce robust results.

3. CONCEPTUAL AR SYSTEM DESIGN FOR EQUIPMENT MANAGEMENT

Accessing large amounts of information in equipment management operations can be facilitated by the dynamics of AR that complement human associative information processing and memory. The proposed AR system is called Augmented Reality-based equipment management system (AR EMS).

3.1 Scenario 1: site monitoring of equipment operation

An equipment manager is standing in an earth-moving construction site wearing video-see-through HMD with a portable computing unit in his backpack and a data glove on his hands (see Figures 1 and 3). When the manager turns on the headset display, a radio frequency identification (RFID) system is activated with read/writable RFID tags mounted onto equipment sending signals to readers connected to the manager's computer. All the equipment located within, say, 46 meters of the manager can be identified and the major working status information is queried from the tags on the equipment. The equipment information is periodically and wirelessly updated by a central server, and the retrieved information can be displayed in the real view of the manager. The displayed information could either be archived data that was previously documented in server and loaded to the RFID tags (e.g., equipment type, manufacturer and capacity etc.) or real-time generated/updated data (e.g., productivity, haul distance, engine temperature, gas consumption, temperature, humidity, etc.).

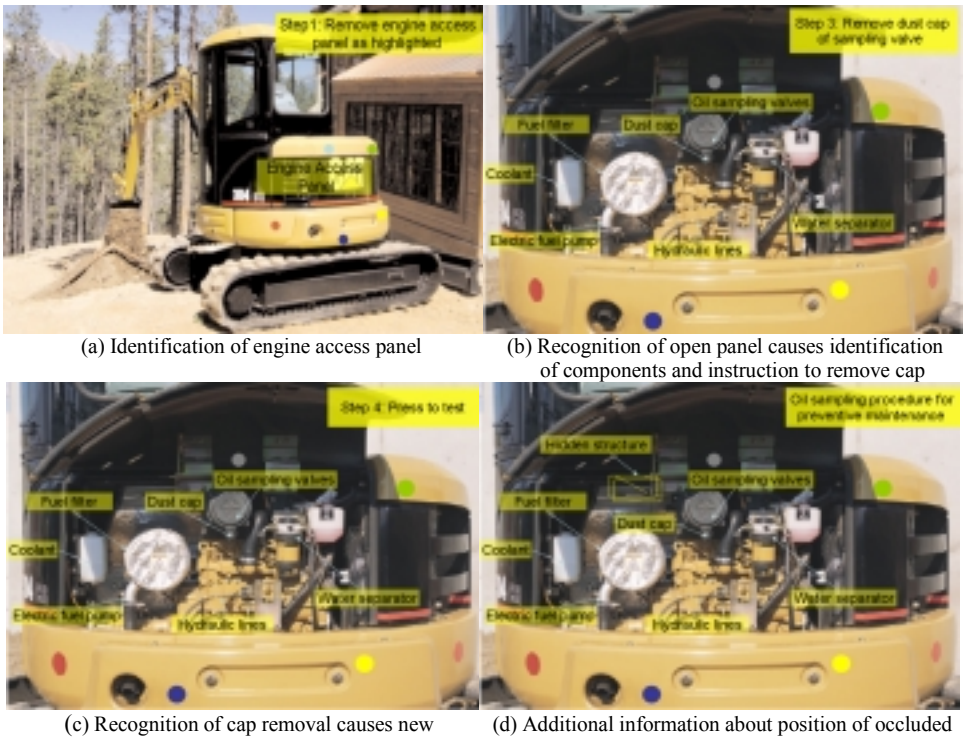
Figure 1. Hypothetical scenario for site monitoring of working equipment

3.2 Scenario 2: close-up inspection of equipment

In a related scenario, the manager can inspect any equipment by physically approaching the equipment. Then, the user is able to browse spatially correspondent digital information about a specific equipment in the course of performing a specific service (e.g., maintenance), or can access interpretive annotations posted by other domain experts or crew members. The user can see virtual icons via the HMD for different functions like identification of equipment components, maintenance procedures, repair procedures, management (performance and

maintenance) history, etc. Upon choosing one icon, for example, maintenance, virtual tags of all components (e.g., tire, engine, etc.) related to the maintenance program for the equipment are displayed right beside their real counterpart over the actual view. Complete records for each component of equipment regarding age, usage, fuel consumption, maintenance and repair costs, down time, and time between component replacements are kept in a database, which can be retrieved by clicking the tag of interest. Also a crew-to-expert communication can be established through wireless LAN (see Figure 3). The maintenance expert sitting in the office can observe what the on-site crew inspects through video and aid in trouble-shooting. He can either instruct the crew via audio communication or send the updated data (pictures, video, and parameters) to the crew's local database through wireless network.

A maintenance scenario that can be implemented by AR EMS is described as follows: The engine of a hydraulic excavator is shown in Figure 2 with varying annotation that is generated in response to the state and context of a simulated 4-step maintenance procedure. The maintenance crew's task is to test hydraulic oil from S.O.S. sampling valves for preventative maintenance. The task sequence exemplifies several of the benefits of AR that were previously described.



(a) Identification of engine access panel

(b) Recognition of open panel causes identification of components and instruction to remove cap

(c) Recognition of cap removal causes new instruction to press test button.

(d) Additional information about position of occluded filter bypass structure in response to user's query

Figure 2. Hypothetical illustration of sequence of automatic instructions and information for maintenance task

A virtual tag highlights the position of the engine access panel to be removed in step 1 (see Figure 2a). The recognition of the open panel causes the identification of components in step 2 (see Figure 2b). Virtual tags appear to identify each component (see Figure 2b). Annotations appear automatically in the camera view, the easy access to information increasing usability. Virtual tags are statically and spatially arranged in the task area for a particular view. Virtual line segments connect each virtual tag to its nearby associated real component. This can elicit the user's attention. Virtual tags relate task information to the context of the work area (callouts identifying hydraulic lines, valves etc.), and guidance on the next action to be performed. The step 3 is to remove the dust cap as indicated by the virtual tag (see Figure 2b). The design of the scene is intended to reduce error by (1) influencing attention and (2) supporting the users' encoding (learning for later recall) of layout and content.

The AR EMS system senses the state of the assembly (the user removed a dust cap in Step 3) and responds automatically with a new instruction: "Step 4: Press to test" (see Figure 2c). Thus, the content of the array directs performance and the interactivity inherent in the system's production of a new instruction contributes to the user's motivation.

Interactive queries are indicated by user selection of an area (see wire frame in Figure 2d) to reveal and identify additional hidden structures related to the

task. This form of interaction demands that the user attend to his or her view of the engine.

3.3 Conceptual design of system architecture

As a test bed to evaluate the above two scenarios, a technology platform, seen in Figure 3, has been conceptualized with a total of seven separate modules shown in Figure 4. The following sections discuss the mechanisms in these modules.

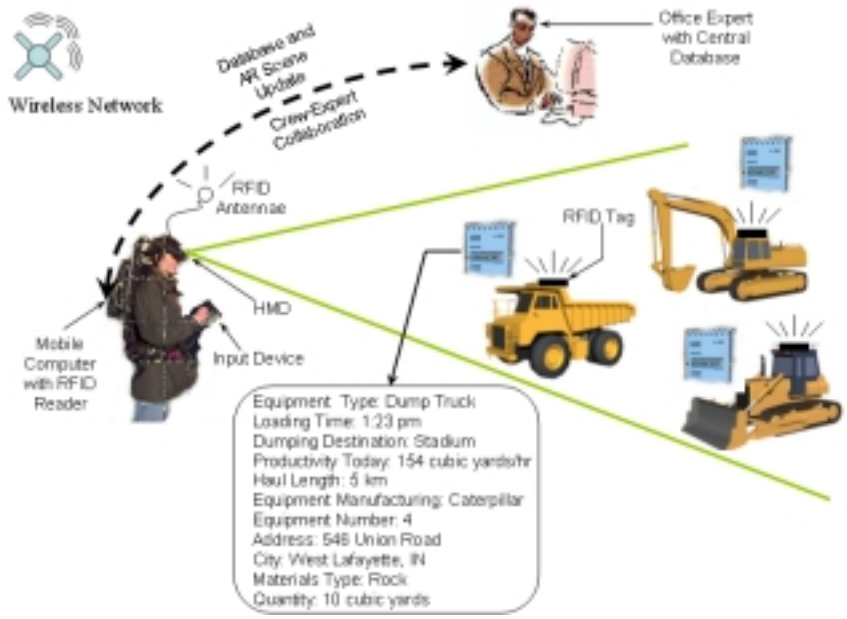


Figure 3. Graphical illustration of AR EMS system application in on-site equipment management

Remote Server Module: Remote server module consists of several experts and a central database server. A service expert sits in an office and provides instructions to on-site management crew whenever necessary via wireless communication. Also, the real-time mixed scene that the on-site crew is viewing can be transmitted to the remote office where the expert can experience the same digitally augmented inspection in the format of a video stream. The data synchronization between databases in RFID tags, and the central database that monitors equipment working condition or service information is made in a real-time manner. Besides the archived data and interpretive annotations posted by domain experts, the real-time produced data (e.g., productivity, haul distance) can also be updated in the database located in RFID tags from the central server. For example, a GPS-based real-time productivity monitoring system can be integrated with the central database and productivity status can be sent to the database associated with each RFID tag and displayed in the user's augmented real world view.

Identification Module: This module uses RFID technology to identify equipment. An RFID tag is mounted onto equipment and signals can be received by readers on the mobile computing unit. The proposed tags are read/writable (R/W) so they can be readily updated.

Display module: ARvision-Stereo HMD, a prototype manufactured by Trivisio Company, is used for display. This HMD is equipped with two built-in color video cameras that are used to capture the real world scene for a video-based tracking algorithm in the close-view inspection scenario. The cameras act as the eyes of users and their position and orientation are tracked by a tracker module. An audio feature that gives warnings or directs attention allocation can also be used.

Mobile Computer Module: This module is located on a high-performance, light-weight laptop and consists of a local database, RFID antenna with reader, and AR software. The *local database* can be accessed by Sybase SQL anywhere as the database query. All of the management data can be stored in the Sybase database. Technical imagery and data about the equipment fleet should be collected in order to compile a comprehensive, equipment-specific database. The *RFID antenna and reader*

Representation module: The media representation in AR EMS is text and/or 2D-image/video. AR EMS can be further enhanced by adding a hypermedia system [7] that provides contextual information in the form of labels and links. Thus, more detailed database information can be retrieved via links as with HTML webpage navigation.

embedded in the laptop collects and transmits the RF signal. The *AR program* is the core technological component of the rendering pipeline for the whole system. In addition to OpenGL and the GLUT graphics library, there are a few software development toolkits (SDK) such as ARTooKit (http://www.hitl.washington.edu/artoolkit/), and an AR software development library—STARlib1.0 [6], etc., which can be readily used as a function library for developing the AR program. The AR program is configured to switch between two functional modes depending on the work scenario: overall site view and equipment close view. The overall site-view mode corresponds to scenario 1 where the user has a comprehensive view of the working equipment fleet and only major working status information is displayed. In this mode, the AR program only accepts the tracker data from a real-time kinematic differential Global Positioning System (RTK-DGPS), suitable for large-area positioning. On the other hand, the equipment close-view mode refers to scenario 2 introduced above where the user is able to closely inspect or observe certain components of the equipment of interest. In this mode, the AR program will switch to fiducial tracking and only reads the tracking information the fiducials provide.

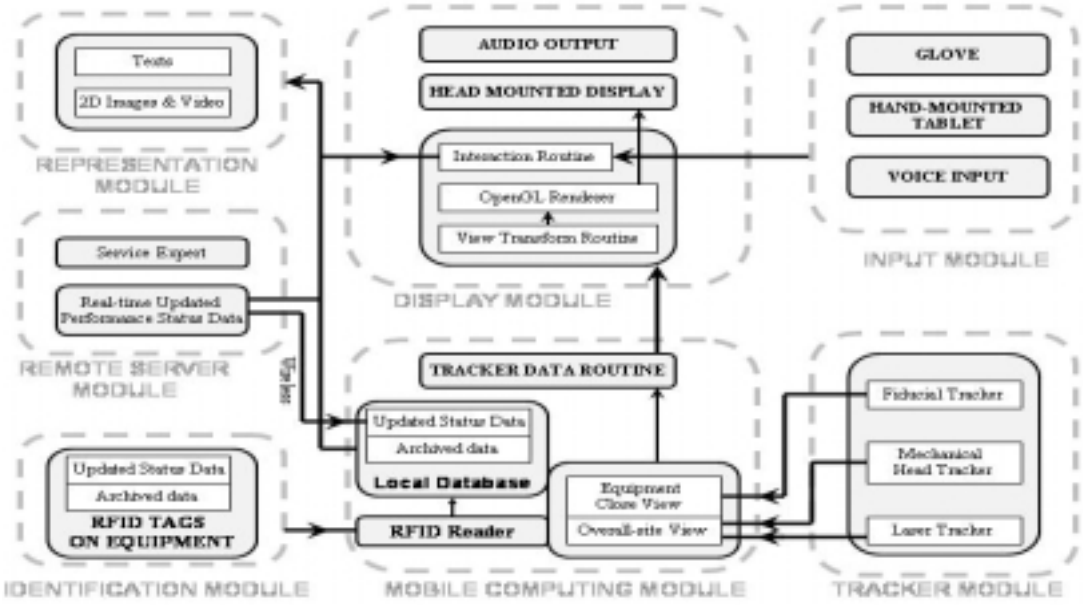


Figure 4. Generic system architecture and data flow of AR EMS

Tracker Module: AR EMS requires a means to track the user and equipment's locations within the construction site. We propose a multiple-tracker solution to realize the two functional modes discussed above. In the overall site-view mode, AR can exploit RTK-DGPS combined with Unscented Kalman Filtering (UKF) techniques [8] to obtain accuracies in the cm-dm range to determine the positions of users and identified equipment. A mechanical tracker fixed the user's body can be used to determine the orientation of the camera on the HMD (the viewing direction). These two trackers can work within the same reference frame and continuously and spatially register the digital information with the video stream of the real scene of the equipment. Instead, in the equipment close-view mode, fiducial recognition can be used for tracking. These fiducials may be LEDs, square markers, dots with a circular pattern, colored dots, or color multi-rings. These routines assume that one or more fiducials are visible at all times; without them, the registration can fail. The way that the system adds labels is that each fiducial beside an object/component identifies the component. After the digital information is loaded, the position and viewing direction of the user are continuously updated by the data obtainged from the tracker. Simultaneously, the digital information image is transformed using location and direction matrices to produce an image that aligns with the objects in the real view.

Input module: This module handles manipulation of the displayed digital content (e.g., clicking hypertext to browse details) and annotates the comments. An annotation function coded into the AR program can enable the user to record comments via a hand-mounted tablet for future reference.

4. CONCEPTUAL AR SYSTEM DESIGN FOR OPERATOR TRAINING

One of the increasingly important application areas of AR is in training and education, where simulation can be used to illustrate concepts and provide exercises that allow the learner to train in a realistic

environment. Compared to real exercises, AR offers reduced costs and hazards and unlimited training conditions/scenarios. This is particularly attractive in heavy construction equipment training. For example, a computer-generated virtual stockpile or piping materials will incur only computational resource costs. In addition, AR allows the creation of unlimited training scenarios (e.g., various terrain, shapes and sizes of virtual stockpiles) providing flexibility without increasing costs. The safety advantage can be realized in many situations such as the simulated fall of elevated virtual materials or equipment tipping due to lifting errors. The proposed training system is called Augmented Reality operator training system (AR OTS), and this technology can be used to increase the number, frequency, and realism of training simulations and offers the means to rehearse future heavy construction equipment operations for actual construction sites.

4.1 Scenario

A front loader operation training scenario using AR OTS is described as an example of how the generic system may function. A novice operator sitting in a real front loader cabin can manipulate the equipment to move a virtual soil stockpile on the ground (see Figure 6a) to a dumping container (Figure 6c) a certain distance away. First, the novice can see virtual tags surrounding their real counterparts and learn the functions of each item on instrument panel (see Figure 5). The novice can follow step-by-step starting procedure instructions or choose to see a pre-recorded training video. Safety instruction will automatically come up with reminders such as wearing a hard-hat, checking the machine and the surrounding area before moving, etc.

Figure 5. Hypothetical illustration of augmented instrument panel with corresponding virtual tags registered to fiducials markers on the panel

Then the novice can start the equipment and move to the virtual stockpile, then position the machine to load soil. The bucket edge position is tracked by laser sensors mounted on it and a wireframe boundary is drawn to represent the bucket in the virtual world understandable by computer (see Figure 6b). The novice controls the loader and the harder he swings the bucket, the faster the bucket passes through the virtual stockpile and a greater volume of soil is loaded. The amount of soil can be controlled by the curvature shaped by the moving wireframe boundary of the bucket while loading. A critical problem to solve here is how to determine the quantity of soil that is taken from the stockpile by the individual bucket pass. Heaping, spillage, and the resistive force from the particular soil type should be accounted in estimating the soil volume. The force-feedback and weight of loaded materials may be "felt" in the novice's hand via a computer integrated haptic device. After the loader finishes one load, the novice maneuvers the equipment to the container on the other side of the work area. Laser sensors on the edge of the container provide data for a virtual wireframe rectangle representing the container's rim in the virtual world. When the novice positions the loader, he or she can start to dump the virtual soil. When the bucket is tilted to a certain angle, the algorithm will understand that dumping should start and then the virtual soil pours from the bucket. If the dumping action yields too much soil falling outside the wireframe rim of the container (missing the target), the system will make comments indicating the poor performance. A performance score could be given as feedback.

4.2 Conceptual design of AR OTS architecture

The experimental test-bed should be established in an indoor facility because current medium-range, high accuracy trackers require equipment setup that may be left in place indoors. Six separate modules were configured and Figure 7 shows the flow diagram for the whole system. The following sections discuss the mechanisms in these modules.

Representation module: Three types of digital content are defined—panel tags, static object, and dynamic object. Panel tag is the descriptive text registered to controls in the cabin instrument panel. The media representation should be text and/or 2D-image/video. A static object is defined as a stationary entity stocked on site such as an untouched soil stockpile. A dynamic object is defined as a moving entity such as loaded soil, the virtual loader bucket edge, etc. Both static and dynamic objects should be rendered in a rich manner because the realistic rendering can provide more cues for essential spatial judgment. Otherwise, the system will fail stimulate proper operator skill development.

Display module: The visual and audio display devices used are similar to AR EMS. A computer-integrated haptic device can provide force feedback

to the operator, which along with the force-control algorithm can enable the novice to feel the simulated force from the "weightless" virtual materials.

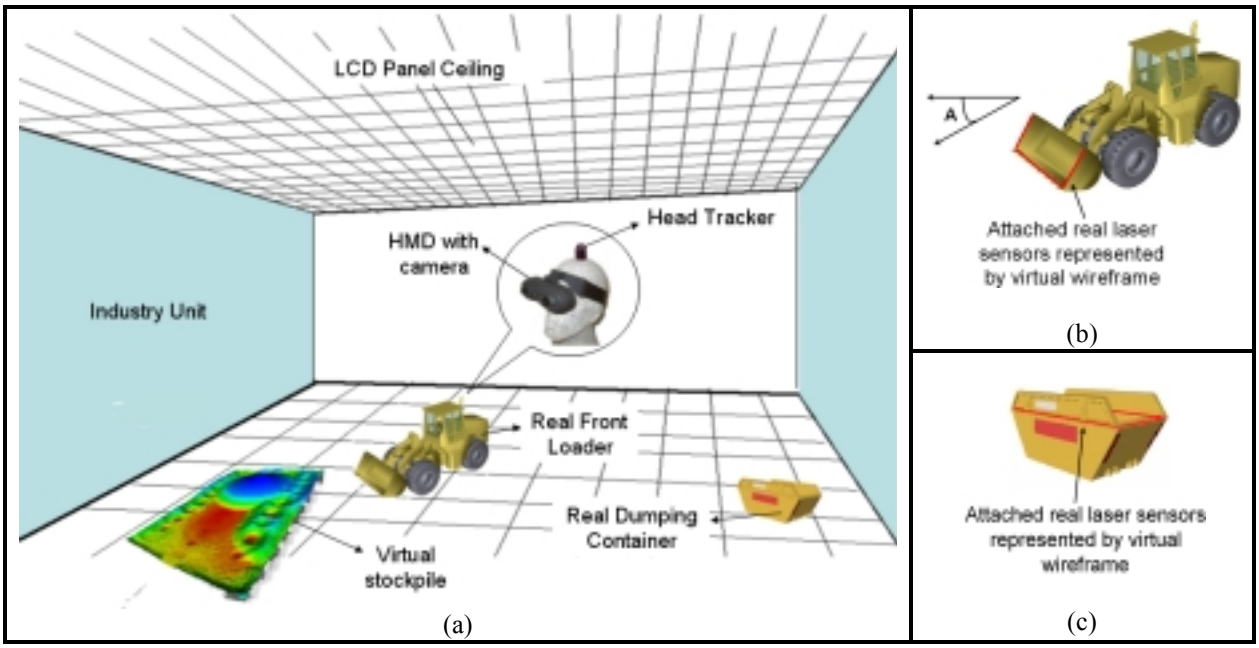


Figure 6. Hypothetical concept illustration of (a) AR system application in loading operation training (b) sensor locations and virtual wireframe representation of real front loader bucket, and (c) sensor location and virtual wireframe representation of real dumping container

Mobile Computer Module: A customized AR program is the core technological component of rendering pipeline for the whole system. More details have been covered in the section of AR EMS.

Tracker Module: The panel tags, static objects, and dynamic objects require multiple-trackers to be combined. Fiducials are to be used for registering panel tags. User's position and orientation (camera) can be tracked by a precise head mounted LED device. With this tracker, the static object can be registered to the location relative to the user. A laser sensor can be added to track the position of dynamic objects (see Figure 6b and c). All of these trackers should be configured according to the same reference, making the static object(s) interact with the dynamic object(s).

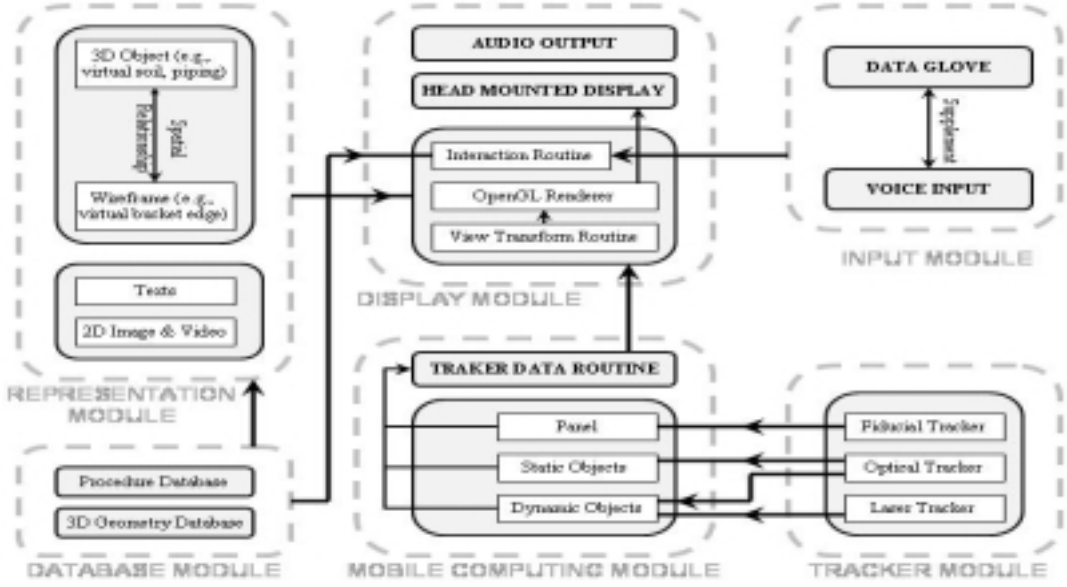


Figure 7. System Architecture Diagram of AR OTS

Database Module: The the local database, similar as in AR IMS, provides detailed training information and procedures for the instrument panel controls.

Input module: A data glove is used to manipulate a virtual 3D cursor and yet not negatively alter equipment operation. Speech recognition can function as a supplement input device for simple command input.

5. CONCLUSIONS

MR is a promising advanced technology for the construction industry that can be integrated into heavy equipment management and operator training. AR can reduce the cost, time, and hazard levels by augmenting these activities with digital content. Two conceptual AR systems (AR EMS and AR OTS) were presented in this paper with detailed hardware configurations discussed, and several selected application scenarios for these two concepts were elaborated.

Acknowledgments

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Graphical Simulation System for Planning and Visualizing Construction Processes

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Abstract: Three-dimensional graphical simulation is very useful for construction planning with its geometric analysis and visualization capability. This technique can further contribute to the improvement of construction planning processes by visualizing the numerically expressed results of process simulation(discrete-event simulation). This paper describes a graphical simulation system that has links to construction process simulation based on mathematical/statistical models. By fusing the visualization capability of the graphical simulation and the analytical superiority of construction process simulation in determining resource requirements and process optimization, the system proposed in this paper can overcome the limitations of the two different types of simulation. Earthmoving operation was selected as a case study to demonstrate the usefulness of the proposed research work.

Keywords: Construction graphical simulation, Visualization, Virtual Reality, Discrete-event simulation

1. INTRODUCTION

Although the usefulness of 3-dimensional graphical simulation for construction planning has been verified [1, 2], it is restricted by kinds of equipment and work to apply this technology to the practice.

In the case of the construction processes of Pick-and-Place method (Picking an object with a fixed form at a certain location and move it to the new place with equipment such as cranes), the geometric analysis with the graphical models can help planners make decisions such as the location, the types and the number of cranes, etc. Graphical simulation can also perform interference checking and constructability analysis for constructing a large number of elements in a small space such as the pipe work in plant construction sites to eventually determine the equipment configurations and construction sequences.

However, the application of graphical simulation has a limitation in dealing with objects without fixed form like earthmoving process. For earthmoving processes, only the approximate visualization might be possible by modifying the graphical models of terrain. However, the amount of earthmoving evaluated by graphical models is not accurate enough if we consider the complicated interaction between the soil condition with large amount of changes and equipment. In this case, the process simulation with mathematical/statistical models about the productivity of the earthmoving processes based on the numerical data of working time, waiting time and working capacity of using equipment becomes effective by performing the resource requirement analysis and the process optimization. The process simulation with mathematical/statistical models (discrete-event simulation) is not fully utilized in the field of construction due to the difficulties of creating models. Therefore, the research for making the modeling processes less difficult has been conducted [3, 4, 5]. In addition, it's also very difficult to make the decision makers of construction trust the numerically expressed results of computer simulation. In order to overcome this problem, Huang attempted to visually prove by differentiating each node of process model in accordance with the change of time and working condition [3]. If the numerically expressed results of the construction process simulation can be visualized with the movement of equipment and materials by using 3D animation, it's not only the expansion of graphical simulation function but also the reinforcement of the process simulation. Kamat and Martinez [6] investigated this topic and developed a 3-D visualization system for construction process simulation.

Another drawback of construction graphical simulation is the lack of the connection with the physical models of the construction equipment and material. The complete description of construction

operations through graphical simulation needs analysis on the physical properties such as the weights, velocity, acceleration of the equipment and material. Hendrikson and Rehak [7] suggested the needs of the physical models for VR (Virtual Reality) -type construction simulation. Beliveau and Dal [8] worked on the theoretical framework to incorporate the physical model into the construction equipment simulation. However, the consideration of the physical phenomena such as equipment's deformation, supporting soil condition, and wind condition requires complex and time consuming modeling process, and real-time analysis is not often possible, which make the incorporation of the physical modeling into graphical simulation unrealistic. Even with the difficulties involved in physical modeling discussed above, certain construction processes such as crane operation require physical modeling to be able to rationally modeled and simulated by construction graphical simulation. The oscillation of the crane's cable and the lifted material that should be considered for improving constructability and safety of the operation is a good example. Current construction graphical simulation systems do not support such physical analysis.

Construction Technology Laboratory at Hanyang University is conducting a research project to enhance the functionality of construction graphical simulation systems. The objective of the research project is to overcome the above-discussed limitations of construction graphical simulation as shown in Figure 1. This paper describes the initial efforts made so far for the visualization of the construction process simulation.

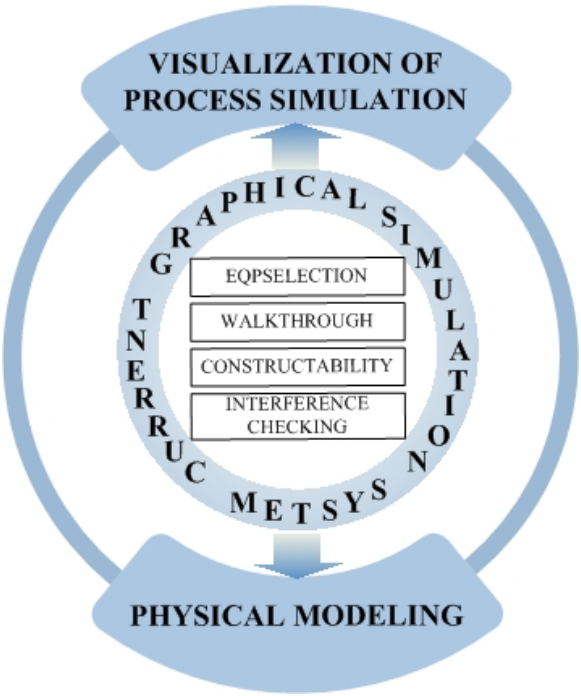


Figure 1. Expansion of Functionality of Construction Graphical Simulation

2. DEVELOPMENT ENVIRONMENT FOR VISUALIZING PROCESS SIMULATION RESULTS

The visualization of construction process simulation was achieved through the links between a commercial discrete-event simulation program SIGMA and a virtual reality program development environment World UP® . World UP® (EAI-Sense8 Products) has been selected as the graphical simulation engine, because of its complete software development and delivery environment for building 3D/VR applications. It also provides an easy-to-use graphical user interface from which creating and/or importing graphical objects and designing simulations. The behaviors of objects were added by writing task scripts using Basicscript language. The task script was written so that the output of the selected process simulation program (SIGMA) could be incorporated for visualization.

3. PROCESS SIMULATION OF EARTHMOVING OPERATION

As a pilot study, the selected construction operation for visualizing the results of the process simulation is earthmoving operation. To get results of construction process simulation for earthmoving process, a model was built using SIGMA. SIGMA, the Simulation Graphical Modeling and Analysis system, is an interactive approach to building, testing and experimenting with discrete-event simulations [9]. The discrete-event simulation model for the earthmoving process has been built through the following procedure.

1) Identify entities and attributes
2) Identify state variables
3) Identify events
4) Specify the relationship among the events

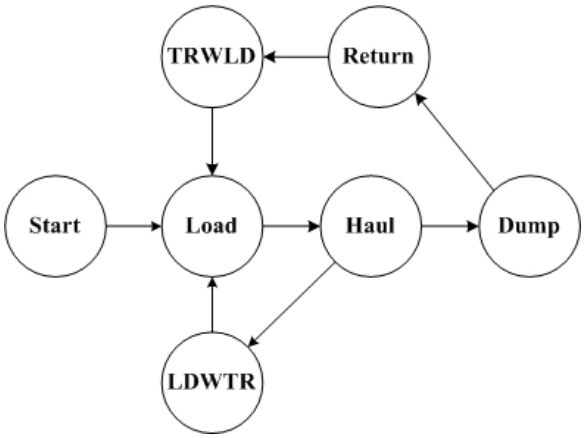


Figure 2. Simplified simulation model for earthmoving in SIGMA

Figure 2 shows the simplified simulation model built through this procedure for the earthmoving process. The following sections describe the details of the modeling procedure for earthmoving operation.

3.1 Earthmoving

Earthmoving is a specialized construction field where large amount of objects without fixed forms are moved from one location, to another location. Earthmoving process can be divided into four tasks, namely, load, haul, dump, and return.

3.2 Identify entities and attributes

The resident and transient entities in the system and their attributes are as follows.
- Loader: Working time, status variable, capacity
- Trucks: Working time at each state, status variable, working capacity

3.3 Identify state variables

The state variable names to the attributes are as follows.
- Status of the loader (Loader: 0/1=busy/idle)
- Number of trucks waiting for the loader to available (Truck)

3.4 Identify events

The changes in the state are called events, and the following events are involved in the earthmoving operation.
- Load: Since the initial status is that the trucks wait for loading by loader, the loader begins loading soil into one of the waiting trucks.
- Haul: The loaded truck departs to haul the soil.
- LDWTR: After the completion of loading, the loader begins to idle.
- Dump: The truck begins to dump in the dump area.
- Return: After the completion of dump, the truck returns to the load area.
- TRWLD: The truck arrives and waits for the loader to be available

3.5 Specify the relationship among the events

This step requires the identification of the dynamic attributes and the state that cause their values to change.
- Load:
  Status of the loader, Loader=0.
  Number of trucks waiting for the loader to be available, Truck=Truck-1.
  Schedule the "Haul" event in the loading time unit.
- Haul:
  Schedule the "Dump" event in the hauling time unit.
- LDWTR:
  Loader=1
  If Truck>0, schedule "Load" event immediately.
- Dump:
  Schedule the "Return" event in the dumping time unit.
- Return
  Schedule the "TRWLD" event in returning operation time unit.
- TRWLD
  Truck=Truck+1

If Loader>0, schedule "Load" event.

4. VISULAIZATION OF SIMULATED EARTHMOVING OPERATION

4.1 The objects-oriented model

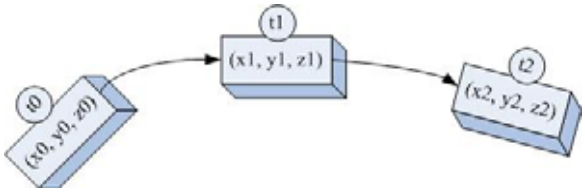
Object-oriented models for equipment, material and work environments for earthmoving operation were devised to effectively visualize the numerical simulation results of the working time, the queuing time as well as the amount resources etc. The interaction between each component of equipment was modeled efficiently, as the equipment behaviors interact with its sub-components (e.g. when the arm of loader is moved up, its bucket should be moved up together) as well as materials that are dealt by the equipment. The same type of equipment can also easily be created with the model hierarchy.

4.2 Link to process simulation

Working time was calculated from the process simulation results such as the start time of load, haul, dump and return. The calculated working time was saved in a text file which becomes the input source to the scripts defining the behaviors of each graphical object.

4.3 Working with task scripts

The behaviors of graphic objects were defined using Basicscript language in World UP program. In order to transport an object in a working time, location and duration information must be defined.



Following pseudo code shows an example of transport an object from location (x0, y0, z0) to location (x2, y2, z2) in end time t2.

```
T= SimulationTime
set obj = Truck1
dim pos as vect3d …
```

```
If T<=(t1-t0) then
   obj.gettranslation pos
      pos.x = x0+(x1-x0)/(t1-t0)*T
      pos.y = y0+(y1-y0)/(t1-t0)*T
      pos.z = z0+(z1-z0)/(t1-t0)*T
   obj.settranslation pos
End if
If (t1-t0)<T<=(t2-t0)
   obj.gettranslation pos
      pos.x = x1+(x2-x1)/(t2-t1)*(T-t1)
      pos.y = y1+(y2-y1)/(t2-t1)*(T-t1)
      pos.z = z1+(z2-z1)/(t2-t1)*(T-t1)
   obj.settranslation pos
end if
        …
```

Here, T, t0, t2 are the system clock, time to start an event, time to finish the event or time to start a subsequent event, respectively. t1 is the time that the object's location would occur at the intermediate point (x1,y1,z1) between the starting and the ending location. The horizontal orientation of the equipment is also continuously updated based on the similar approach shown above. The pitch and roll of the truck should also be updated based on the terrain shape. The algorithm for this process is currently being developed. The scripts for truck, loader, and soil were implemented to visualize the dynamic earthmoving process based on the result of the process simulation. Figure 3 shows the overall hierarchy of the graphical simulation system for earthmoving process, and Figure 4 shows a scene of the earthmoving process visualized by the developed system.

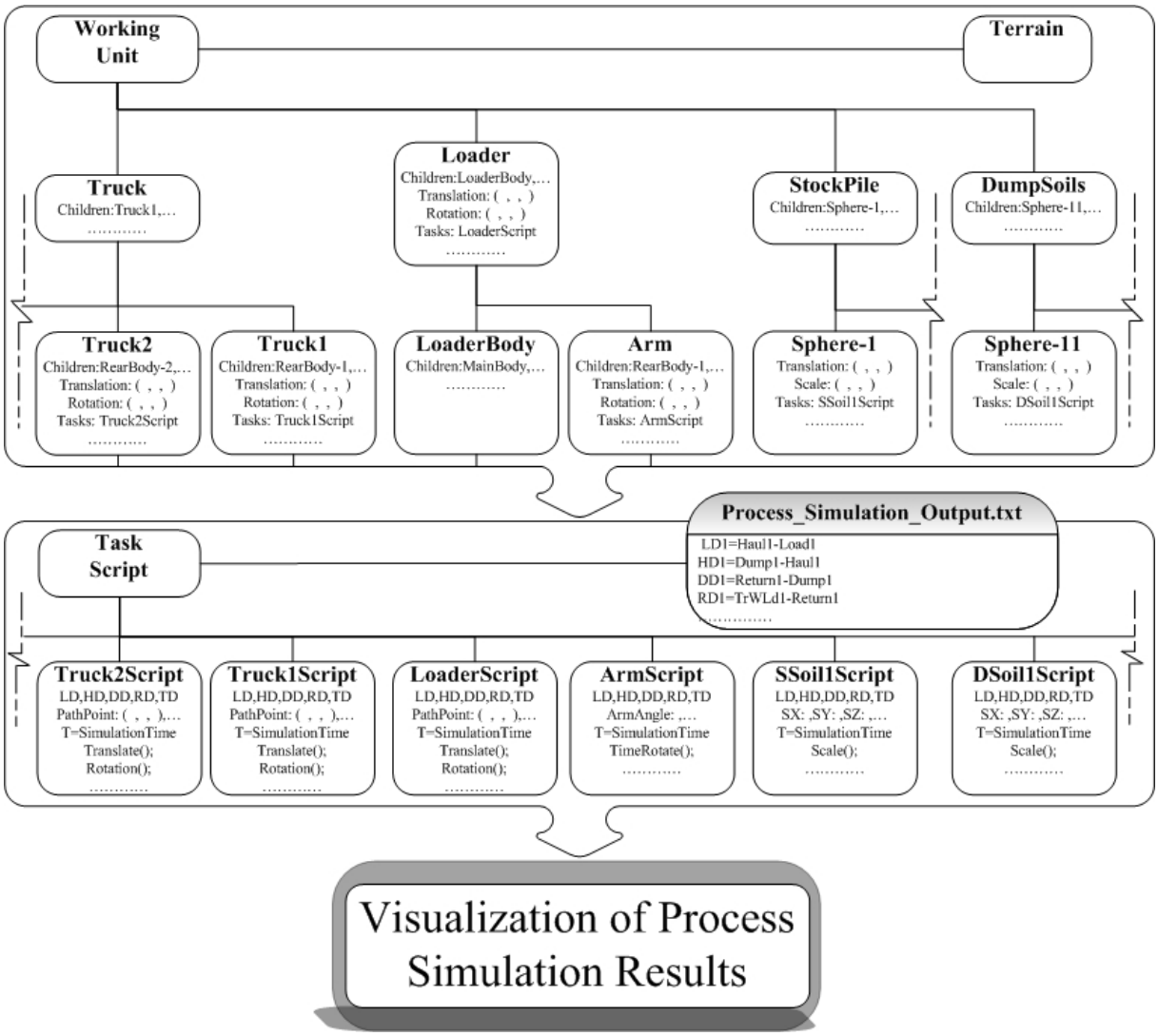


Figure 3 . Graphical simulation system for earthmoving process

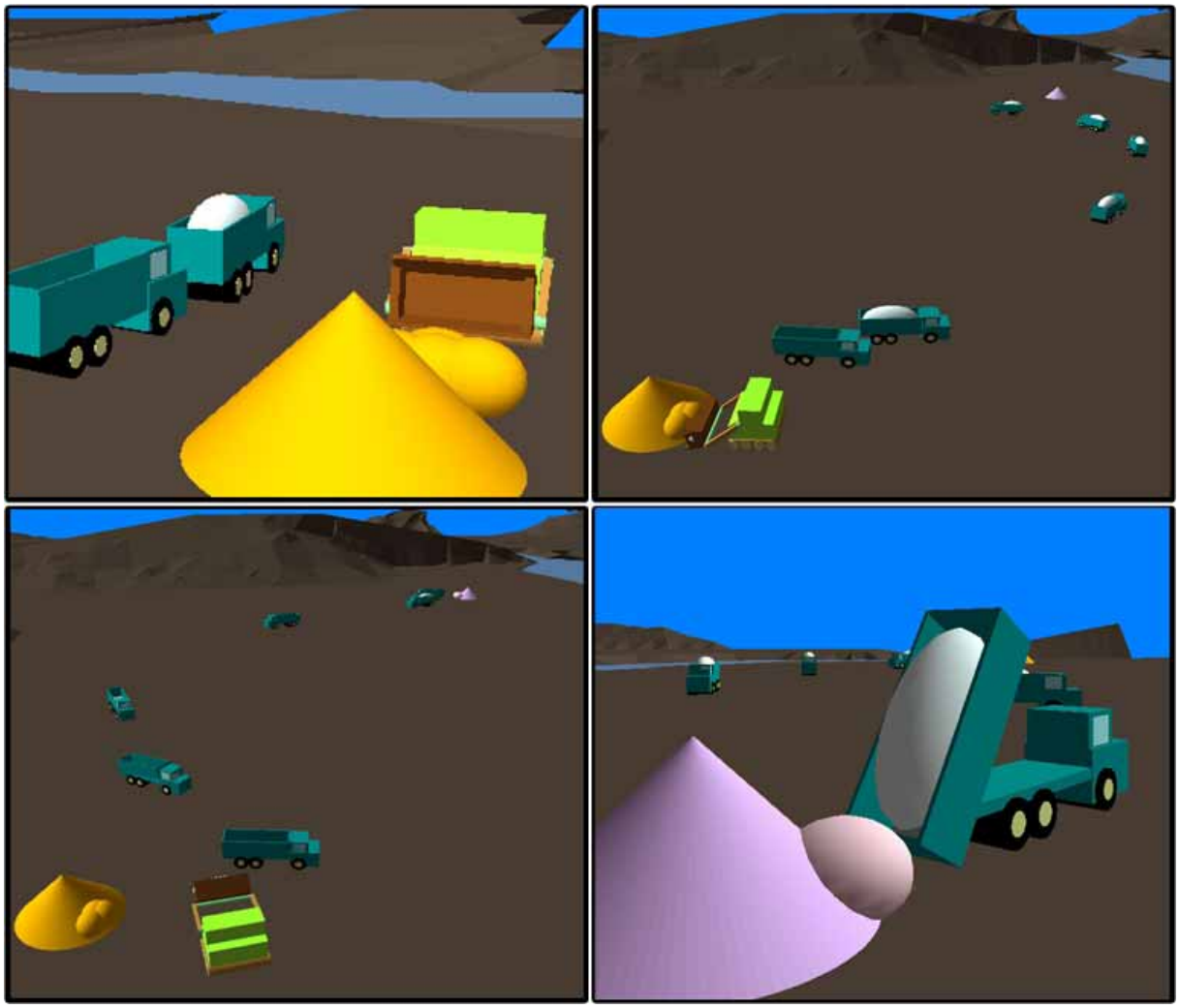


Figure 4. Scene of earthmoving process

5. CONCLUSIONS

The major objective of this study was to develop a graphical simulation system that can help the construction planner in the design and planning of construction processes. In order to meet major objective, the visualization of earthmoving process was achieved through the links to the discrete-event simulation system. The case study revealed that the credibility of the discrete-event simulation results could be improved with the realistically visualized construction operation.

Acknowledgments

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SIMULATION OF CONSTRUCTION PLANNING OR HIGH-RISE RC BUILDINGS A PROCESS PLAN CONSIDERING OVERTIME WORK

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Abstract: The study is aimed at better planning the cycle process that considers production characteristics in high-rise RC building construction and at establishing a better method by a simulation system using computer-aided tools. A special emphasis of this study is placed on examining the effect for shortening the cycle term of site works and the influence from overtime work on the productivity where situation of such real projects is taken into consideration. Furthermore, we examine choices of optimal working patterns even considering some additional labor cost generated by overtime work.

Keywords: High-Rise RC Building, Simulation, Cycle Term, Line Balancing, Resource Leveling, Overtime Work

1. INTRODUCTION

There are a variety of practical methods applicable to the process-planning phase of construction work. An increasing trend in developing construction work plans to consider the repetitive type of work, where the site work requires repetitive application of the same work process, particularly in such aspects as the need to suit the high-rise building construction or the mass construction of housing complexes. Besides, attempts to intentionally increase the repetitive cycles by segmenting the project sites for such purposes as boosting productivity and realizing shorter layoff periods for field workers. As compared with other types of construction work, the repetitive type of process by nature can be seen as readily subject to those production planning methods being widely used in manufacturing industries, making it possible to more systematically plan and execute the construction work.

With a simulation system for better planning and managing the work and processes of construction projects using a computer-aided support tool, this paper is aimed at establishing a method of systematically improving construction planning activities in high-rise RC building construction work for developing multiple dwelling-type housings.

Conventional studies over the process planning activities for high-rise building construction work have been based on actual data collected from the established “regular work schedules,” that is, man-hour data accumulated only between the daily starting time through the closing time. So far, few case studies has been made covering “early bird extra work” and “evening overtime work,” which are often needed on the first-line worker levels trying to “adjust” their daily work volume as such. In this study, by considering such on-going work-site realities and incorporating such overtime work data as aforementioned, the authors intend to look at the process improvement phase by means of an evaluation index in terms of the effect of shortened work cycles and degrees of productivity fluctuation. More specifically, this entails 1) a review to set the timing as to when to change the construction cycle term for the basic-floor construction work-cycle on the premise of the production characteristics of the type of construction project, and 2) evaluation of decision-making possibility as to selection of field work patterns.

2. PROCESS SIMULATION SYSTEM

2.1 Functions of the Process Simulation system

The system being introduced hereunder is a construction system simulation system by which the process to reduce time span needed for the any standard floor pattern work-cycle can be logically calculated electronically. It considers on-going quantitative changes in required materials and the accumulating learning effect. Also, it has a process-adjusting function that purposely incorporates overtime work. It can also evaluate the work plan through use of such data as balance loss and indices of working smoothness and leveling of labor fluctuation. Further, it compares ups and downs in the total construction schedule and total labor cost, so as to determine priorities for either schedules or labor cost aimed at realizing an optimum process plan.

2.2 Simulation System Structure

The software used in our basic system is MS Excel for the spreadsheet program, combined with MS Project as the project management software. As shown in Fig. 1, its nucleus is a database covering information about construction materials to be used, specific work items and required workforce. Visual Basic for Applications software is used in automating spreadsheet operation.

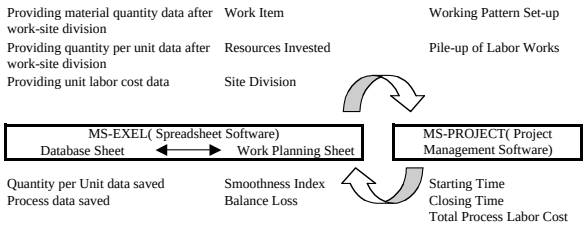

Fig. 1 The Structural Sketch of the Simulation System

2.3 Establishing Constraint Conditions

The basic regular daily working hours is set at 8 hours, being allocated for 4 time-units of 2 hours each (i.e. a one-quarter day work-unit). Also, a maximum of 1 hour per day of overtime work is allowed. Specifically, early-bird overtime can be scheduled between 7 to 8 a.m. or a dusk overtime between 5 to 6 p.m. The daily regular work period is set at 8 hours a day. A maximum of 1 hour per day can be allowed as overtime work, which should fall under one of the following four patterns:

Pattern I: Regular work during the scheduled 8-hour period

Pattern II: Overtime for 1 hour per day by a molding worker

Pattern III: Overtime for 1 hour per day by a reinforcing bar placer

Pattern IV: Overtime for 1 our each by both a molding worker and a reinforcing bar placer

Evaluation of the process involving different Patterns is done in terms of the additional labor cost necessitated by the reduced number of work-days of the cycle term and the needed overtime work. To specify the work-to-work connections, an accurate state of on-going works is demonstrated by combining the use of 1) the pile-up type "finish-start" (FS or a work started upon finish of the previous work) link and the "start-start" (SS or a work started along with the start of the previous work) and of 2) the allocation type "start-start (SS) + "lag-time" set-up. Also, another restraint is imposed on the concrete work to be definitely complete the concrete-placing work in one day.

2.4 Simulation Flow

2.4.1 STEP 1: Developing the Database

Fig. 2 shows the flow of this Simulation System.

A number of database sheets to be used in each segment of site work are developed in this step. Data for [Materials Quantity Sheet] is produced for each part of the required work, where quantity units to be used are determined according to the Building System as a mixture of the physical contents of the building with their corresponding work methods. Also, when the work-site is divided, each segment is set up with the materials to be used there. [BUGAKARI-setting Sheet (Unit Quantity-setting Sheet)] shows the trend of Unit Quantities based on the learning curves that were derived from Work Measurement. It can be determined according to the selected floor, Unit Quantity on that floor, and the degree on the Learning Curve. Data on the [Resource Sheet] establishes Worker(s) as "Resource Names" and Standard Labor Cost of each named worker.

2.4.2 STEP 2: Work Plan

The [Initial Set-up Screen] sheet determines such factors as "forecast conditions of the object floor," "number of work area segments," "segment-to-segment work connections," and "work characteristics of each work segment." Specific information about Work Characteristics such as "Serial Work Number," "Outline Number," "Part of Work Section," "Name (description) of Work," "Preceding Work," "Work Connection," "Crane Need," "Yard Work Need," "Related Job Titles," "Number of Work-team Members," and "Number of Work-teams" are manually entered. Such factors

as Project Name, Number of Segment of the Work Section, Segment- to-segment Connection," (indicating the starting time for the next work section), and Forecast conditions of the Object Floor (Start and Finish)," are specified. Then, information about all work items per floor to be worked on, work characteristics of each work item, data from "Material Quantity sheet" and from "Unit Work Quantity," are shown on the screen (all in line with the set-up status of Labor Database and Work Characteristics sheet). This should automatically provide estimated length of Work-time. Then, the data is visually "redesigned" so as to permit easier import with the Project Management software. The completed sheet is now kept on file.

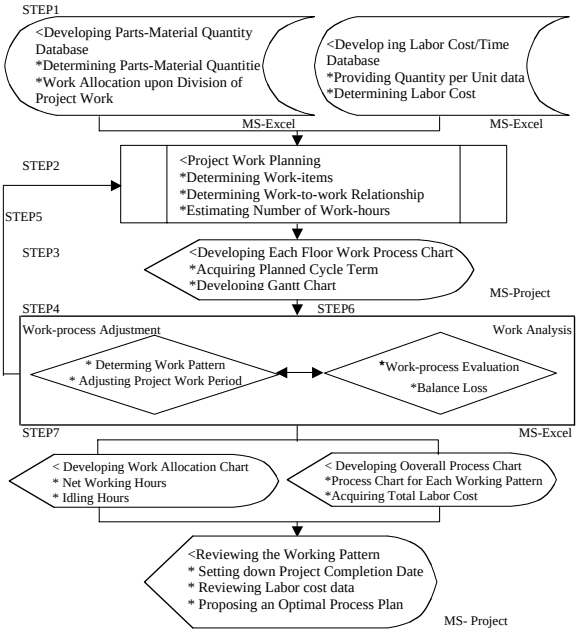

Fig. 2 Simulation Flow Chart

2.4.3 STEP 3: Preparing Work-process Chart for Each Floor

Here, the Database sheet completed with spreadsheet software is imported to Project Management software, where specific Work Period for each floor is automatically figured out. Also, Staring/Closing Hours and project's Labor Cost data are obtained, and the final data is kept on file as spreadsheet. Process chart for each floor is automatically produced and filed as a Project Management file. The daily calculation of Labor Cost here is rendered in terms of workers' hourly pay.

2.4.4 STEP 4: Work-process Adjustment

Along with the calculation being performed during Step 3, Loss Time in each "between-works interval" too is figured out. If any improvement action becomes necessary based on the loss time data obtained, a return to Step 2 becomes necessary so that the conditions of between-works inter-dependency (in terms of Lag Time) is automatically altered, and a new process planning is made with the basic floor. The same routine is repeated from the ground floor to the top floor. Finally, the cycle term applicable to each floor is determined with specific start/close hours and related labor cost data figured out.

2.4.5 STEP 5: Work-process Planning

This step includes a return to Step 3 where four working patterns can be established based on the combinations of work for molding workers and reinforcing bar placers on the Main Menu of the Project Management software. Also, labor cost data such as Unit Labor Cost and Work can be re-entered directly on the screen. With specific working patterns determined, the system now automatically figure out the total project work period and labor cost along with the material/labor database and the specific Work Characteristics set-up information.

2.4.6 STEP 6: Work-process Evaluation

In evaluating any work-process, the common practice is to use the data of the number of days required and productivity (such as unit quantity). The system we are discussing is unique as it applies two types of index as being used among manufacturing circles: 1) [Balance Loss] that indicates to what extent the work arrangement contains idle or non-productive time elements, and 2) [Smoothness Index] that reflects uneven work-hours. Even if the work-process contents show gradual changes because of reduced materials or of some learning effect, the system can count the number of idle-hours through obtaining Balance Loss information.
Balance Loss is mathematically expressed as follows:

$$BL_{ij} = \frac{\sum_{k-1}^{n}(c - t_{kij})}{nc} \times 100$$

Here, a = number of work stations, c = number of cycle hours, t_k = total working hours on the k_{th} working day (i.e. aggregate total of all element hours).
Smoothness Index is mathematically expressed as follows:

$$SI_{ij} = \sqrt{\sum_{k-1}^{n}(t_{maxij} - t_{kij})^2}$$

Here, t_{max} is maximum working hours on the day [n], as resulted from allocation of work elements. Finally, this step

graphically displays on-going trend of Balance Loss and Smoothness Index for all stories as well as by work-sections and by job-titles.

2.4.7 STEP 7: Analysis of the Final Results

Aimed at making the task of work-process management easier, this system compares work-hours between the materials used, analyzes the learning effect, and make the results visible in several ways: "Process Evaluation Graph," "Work Allocation Chart," "Table of Total Process Labor Cost," "Overall Process Table," and "Work-process Planning Table for Each Working Pattern." These means help identifying to what floor is best for moving in and for what job titles should the process improvement best address.

3. SIMULATION APPLIED TO ACTUAL BUILDING CONSTRUCTION

Based on the actual data accumulated in the system, the construction process of the basic floor is simulated so as to validate and analyze the system itself in specifying 1) the effect of reducing the cycle term for each of the four Work Patterns; 2) process evaluation in terms of labor cost increase/decrease for overtime work; 3) process evaluation as reflected in Balance Loss and Smoothness Index; 4) evaluation of optimum planning of work-process.

Table 1 is a summary of the construction work of a high-rise multi-dwelling RC building as applied by our simulation system. The work represents a system construction as an improved type of the conventional method of construction work. The simulation treated those work items as found "on a group-work level," dealing with a total of 34 items, the breakdown of which is: 1) 19 items of molding work per work segment; 2) 8 items of steel bar placing work; 3) 2 items of pressure welding; 4) 2 items of scaffold worker; 5) 3 items of earth work (see Table 2). Generally speaking, construction work of high-rise RC buildings consists of joint-works among workers with a number of different job-titles that is a relay of work from molding, steel bar placing, facility/plumbing work, through concrete work. In studying the work under this system, we intended to make the connections among the related works in the actual construction process well reflected. Specifically, the molding work is treated with its [Setting out] through [Floor mold insert] steps as one "bunch of works," and the steel bar work with its [steel beam crane and set] through [steel pillar crane and set] steps as another "bunch of work," for which the 1/4-day unit time is allocated appropriately. Fig. 3 illustrates the 7-day cycle term of such work processes. To help the actual construction process reflected better, drawing issue, rate of learning curve, actual quantity of materials and work unit for the intended cycle term are used. As for the ratio on the learning curve, the data of certain similar precedent case was considered. The Unit Labor Cost is calculated based on the published public labor cost data: Using its standard labor cost (daily rate), Unit Overtime Labor Cost per Hour is calculated as [Daily Unit Labor cost /8 x 1.25]. The simulation applied to the basic floor construction process based on the data of material quantities, unit labor cost and BUGAKARI (quantity per unit), and rates on the learning curves has resulted as follows.

Table 1 Construction Project Outline

Location	Minato-ku, Tokyo
To be used for	Multi-dwelling type housing
Total construction Peiord	April 1, 1998 ~ November 15, 2000
Architectural structure	RC
No. of floors	32 floors + 1-fl. basement + 1 tour-house
Total space of the cite	6,177.41m^2
Building ground space	2381.02 m^2
Aggregate floor space	38,999.13 m^2
Maximum height	99.5m
Construction Methods	Pillar・beam:frame: Simplified system
	Pillar・beam:steel bar welding: Automatic gas pressure-welding:
	Floor: steel bar built-in steel deck floor
	Balcony & misc.: Half PCa
	Concrete: Strength (mx)24~54N/mm^2, concrete placing by pump
	No. of Work-site divions: 2
Use of Cranes	Tower cranes: 2 units (120 tons)

Table 2 List of Work-items used in the simulation

Frame-molding work	Beam & floor/Frame/Fastening	Beam/Steel bar/Drop set
Total structure/Molding frame/Setting out	Floor/Frame/Stepped frame	Floor/Steel bar/Bar arrangement
Pillar/Frame/Build-up	Floor/Floor support/Unloading	Pillar/Steel bar/Crane & set
Pillar/Frame/Fastening	Floor/Floor support/Unloading	Beam/Steel bar/Unloading & Field pre-assmbly
Beam/Beam support/Crane	Pillar/Frame/Unloading & disassembly	Pillar/Steel bar/Unloading & Field pre-assmbly
Beam/Frame/Crane & set	Beam/Frame/Unloading & disassembly	Erection&Scaholding
Beam/Beam support /Set	Pillar/Frame/Preparation	Total/net/climbing
Floor/Floor support/Crane & set	Beam/Frame/Preparation	Stair/Stell frame/Setting
Floor/Frame/Crane & set	Steel bar work	Concrete placing
Floor/Frame/Insert	Pillar/Steel bar/Hoop bar finish	Total/Concrete/Molding to joint between work-site divisions
Balcony/PCa/Temporary setting	Beam/Steel bar/Crane & sedt	Total/Concrete/Preparation for placing
Balcony/PCa/Welding	Beam/Steel bar/Binding the pressure-welded part	Total/Concrete/placing

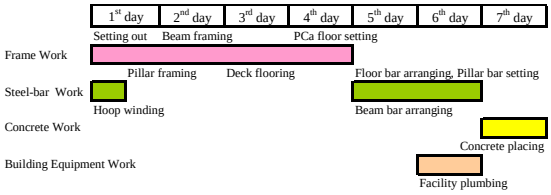

Fig. 3 Cycle Term Process

Fig. 4 represents the result of simulation of the cycle term for

each work pattern. In each case, the cycle term is seen as reduced due to learning effect and other causes. Fig. 5 & 6 are cases of the cycle terms at the 25th & 28th floors with each work pattern. In consideration of lunchtime recess and other scheduled rest-time at the construction site. The time allocation by 1/4 day unit is used within the regular 8-hour work schedule.

Table 3 Labor Work & Cost Data

Type of Work	Learning Ratio (%)	Average Daily Attendance (Person)	Unit Labor Cost (¥/person/day)	Unit Overtime Cost (¥/person/hour)
Framing Work	85	15	19,200	3,000
Steel Bar Work	85	12	18,900	2,900
Scaffold Work	95	8	18,400	2,800
Concrete Work	95	8	18,600	2,900

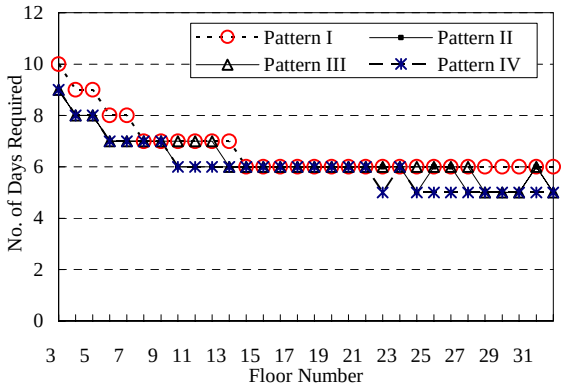

Fig. 4 Cycle Term by Different Work Pattern

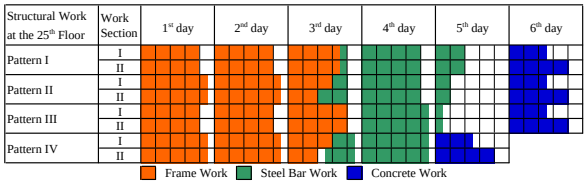

Fig. 5 Allocations of Work Segments at the 25th Floor

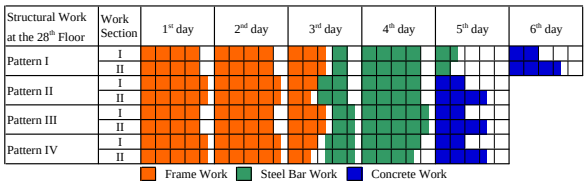

Fig. 6 Allocations of Work Segments at the 28th Floor

In the case of the work on the 25th floor, the cycle term by Pattern I is 6 days, as well as by Patterns II and III. The cycle term for Pattern IV, however, can be apparently reduced to 5 days. In the case of the 28th floor, the cycle term for Pattern I is 6 days. The cycle term for Patterns II, III and IV can by all means be reduced to 5 days because the overtime work largely make the steel bar work and the concrete work to come closer with each other. In other words, with molding workers or steel bar workers doing overtime for 1 hour, concrete workers' idling time can be well reduced. It is found that the cycle term can be reduced as a result of effective utilization of workers' increased working hours. The simulation applied to each Work Pattern resulted in considerably reducing the number of necessary workdays when compared with 200 scheduled days for Pattern I as follows:

Pattern II: 186 days (14 days saved)
Pattern III: 190 days (10 days saved)
Pattern IV: 191 days (9 days saved)

Incidentally, there were some "temporary ups and downs (plus & minus)" in these patterns as affected by temporary ups and downs in material supply. Data on Table 4 shows such plus/minus Figures as reflected in "Required Number of Cycle Term Days," "Cycle Balance Loss" and "Labor Cost-Plus/Minus (unit: ¥10,000)," respectively.

Table 4 Workdays Required & Cycle Balance Loss & Labor Cost Increase/Decrease

Floor	Workdays Required				Cycle Balance Loss				Labor Cost Increase/Decrease (Unit: ¥10,000)		
	I	II	III	IV	I	II	III	IV	II	III	IV
3F	10	9	9	9	7.98	4.30	1.96	7.88	-11.6	-5.3	-7.4
4F	9	8	8	8	8.33	3.04	1.47	6.94	-2.0	-5.3	2.3
5F					11.50	6.46	4.80	10.12	-13.1	-5.3	-8.9
6F	8				9.64	0.88	1.82	5.61	6.0	-6.7	10.2
7F		7	7	7	12.24	5.33	4.67	9.50	6.0	-6.7	10.2
8F					3.07	8.21	7.50	12.25	6.0	4.2	10.2
9F	7				3.10	8.44	7.72	12.28	6.0	4.2	10.2
10F					8.60	13.57	13.96	3.15	6.0	4.2	-0.7
11F					10.42	2.17	14.14	7.81	-14.6	4.2	-11.8
12F		6			12.14	3.69	15.80	8.43	-14.6	4.2	-11.8
13F			6		11.22	2.10	0.51	6.08	-14.6	-6.7	-11.8
14F				6	0.97	6.91	4.65	10.12	-5.1	2.8	-2.3
15F					2.43	8.27	6.05	11.42	-5.1	2.8	-2.3
16F					3.75	9.49	7.31	12.59	-5.1	2.8	-2.3
17F					5.87	10.68	12.12	13.73	4.5	2.8	7.3
18F					2.83	7.47	9.55	12.19	14.0	2.8	18.2
19F					7.22	11.32	12.04	15.68	14.0	2.8	18.2
20F					8.19	12.23	12.97	16.54	14.0	2.8	18.2
21F					9.10	13.06	13.84	17.35	14.0	2.8	18.2
22F				5	9.97	13.87	14.68	2.10	14.0	2.8	7.3
23F	6			6	7.60	11.45	12.64	16.02	14.0	2.8	18.2
24F		5			11.56	1.03	16.21	3.55	4.5	2.8	7.3
25F		6			9.90	14.06	16.15	1.39	4.5	4.2	-2.2
26F		6			10.90	15.05	15.26	2.74	4.5	4.2	-2.2
27F					12.22	0.59	16.49	4.15	-5.0	4.2	-2.2
28F		5		5	13.40	0.97	0.97	5.41	-5.0	-6.7	-2.2
29F			5		14.03	1.65	1.81	6.07	-5.0	-6.7	-2.2
30F					14.58	2.27	2.45	6.67	-5.0	-6.7	-2.2
31F		6	6		10.59	14.52	15.20	2.41	4.5	4.2	-2.2
32F		5	5		17.78	6.01	5.95	10.07	-5.0	-6.7	-2.2
	200	186	190	181					26.0	6.3	79.5

The "Labor Cost--Plus/Minus" column clarifies how Labor Cost can be increased or decreased by saving 1 work-day of the Cycle Term. If workdays for both molding workers and steel bar placers are reduced by one day, a maximum of 19 workdays can be saved while the labor cost increases by ¥8-million. 3rd, 5th, 11th, 12th, 13th, 14th, 15th, and 16th also, it is noted that the expected effect of overtime work varies by job-titles. For example, under the time goal of construction set at 185 days, overtime is scheduled for molding workers on the 3rd, 5th, 11th, 12th, 13th, 14th, 15th, and 16th floors, and for steel bar workers on the 4th, 6th, 7th, 28th, 29th, 30th and 32Nd

floors (ref. Table 4), where total of 15 workdays can be saved and a minimum cost increase can be realized. Thus, the authors succeeded in developing a methodology by which an optimal combination of overtime for workers can be realized.

Fig. 7 graphically illustrates difference in Balance Loss of work-process between Pattern I and pattern IV. The higher the floor goes up, Balance Loss is seen also rising, but is seen reduced at each point of work-process improvement. So is workers' idle time, too. It also shows that maximum rate of Balance Loss for Pattern I was about 15% which is equivalent to some 8 hours work on the 7-day work-process. This situation was caused by the concrete-layers' 1-day assignment on the last day only of the Cycle Term, making them unable to reduce their idle time in excess of the 1/4-day allocation limit on the previous workday. It can be seen with Pattern IV that a 6-day Cycle Term was realized on the 10th floor and a 5-day Cycle Term on the 24th floor and above. It means a process improvement in overtime work reducing balance loss. However, on the 14th through 21sr floors, Cycle Terms could not be reduced making idle time increase, and so it was meaningless to let them work any unscheduled overtime. Thus, it can be said that Balance Loss data can serve as a valid index in examining the possibility to reduce Cycle Term.

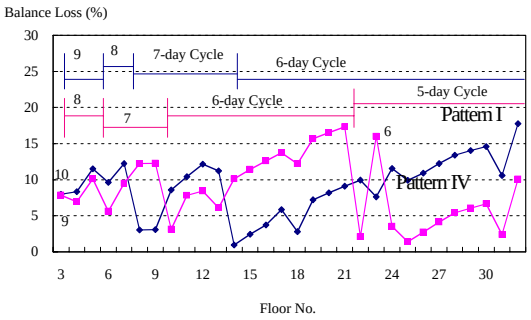

Fig. 7 Balance Loss Curves

Fig. 8 represents a total work-process plan developed by selecting an optimal pattern for each Cycle Term based on the Balance Loss and Smoothness index data for the four established Work Patterns. It resulted in a straight reduction in the Balance loss for all Cycle Terms at 10% or less. Specific figures for Smoothness Index (SI) came up as SI =2.12 on the 3rd floor, SI = 3.05 on the 32nd floor, and up to a maximum value of SI = 4.54 for all floors. Table 5 compares the Standard Work-process and an Optimal Work-process in terms of Cycle Term, Total Man-days, Total Man-hours worked and Total Cost resulting from the simulation. It clarifies that, within the same total working time, shorter Optimal Cycle Term, workers' Total Man-days and reduced Total Labor cost. Our simulation test, as described above, searching for optimal work-patterns and their appropriate combination, verified that project's work speed were stepped up and stabilized, and both labor and materials as supplied proved effectively utilized.

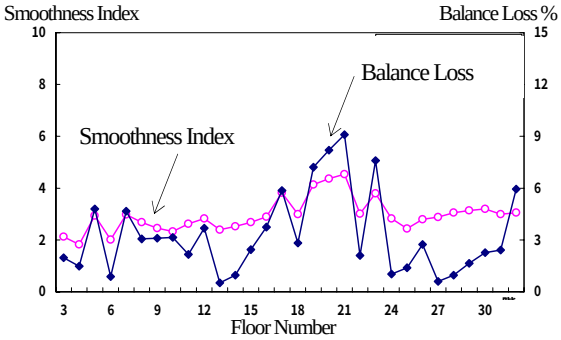

Fig. 8 Balance Loss and Smoothness Index Curves

Table 5 Comparison of Standard Work-process and Optimum Work-process

	Total Term (days)	Total Attendance (man-days)	Total Working Hours	Total Labor Cost (Unit: \10,000)
Standard Work Process (Regular Schedule)	200	5,200	43,426.9	9,838.1
Optimum Work Process	181	5,020	43,426.9	9,690.0

4. CONCLUSION

In this study, a construction planning phase for high-rise RC housing was simulated by a computer-aided tool. By focusing the study on overtime work in examining the possibility of process adjustment, the simulation was made more realistic. It resulted in assuring the effect of reduced cycle terms for workers by intentionally and smoothly allocating overtime. It also made it possible for any ineffective overtime plans to be constrained. Besides, we could propose a methodology to single out optimal combination of work plans based on the labor cost data forecast.

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APPLYING SIMULATION TECHNIQUE TO MODEL DESIGN ITERATIONS

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Abstract: Improving the scheduling of the design project can greatly reduce the total duration of the project. However, appropriately representing the schedule of a design project is complicated chiefly because the design activities often have different degrees of information dependencies between each other. That is, design process involves a number of iterations across the design activities. This work develops a simulation-based model to incorporate the design iterations for generating the schedule of a design project. The proposed model is implemented using a simulation language and the benefits of the model are demonstrated by an example project.

Keywords: design iteration, simulation, design schedule, and design process.

1. INTRODUCTION

Many scheduling models have been developed to manage the duration of a construction project, but little effort has been made to control the schedule of the design project. However, slightly improving the control of the design schedule may greatly reduce the total duration of the project. Glavan and Tucker pointed out that about one third of public and private A/E project missed cost and schedule target for some design-related problems [1]. A recent survey demonstrated that success of design process was the key to the success of project in the UK [2].

Current practice typically uses a bar chart method to represent the schedule of a design project. In the bar chart, each bar covers several months and represents a design activity. Some responsible project managers may further state points of expected percentage completions (such as, 25%, 50%, 75% and 100%) or control points (for example, drawing begun, drawings ready for engineering review, signing by project manager, incorporation of client's comments, and ready for bid/construction) as milestones in each design activity. Unfortunately, construction projects are frequently delayed because design deliverables (such as drawings, specifications, material take-off sheets and others) are delivered late.

Alternatively, a critical path method (CPM) network analysis may be used to schedule design activities. However, using CPM analysis for design projects is difficult mainly because design activities frequently have different degrees of information dependencies between each other. Namely, the design process involves a number of iterations. Thus, a large amount of design information passes among activities many times until owner's needs or regulatory requirements are met. Such iterative information dependency makes difficult to define the logical relationships between activities in the network as well as to evaluate the duration of each activity. Additionally, design resource utilization and productivity of designers are not easily incorporated into the schedule of a design project.

This work develops a simulation-based model to incorporate the design iterations for generating the schedule of a design project. The benefits of the model will be demonstrated by applying the model to a practical design project.

2. PAST REARCH

Considering design iterations and information dependency, Austin et al. [3-4] described a planning methodology (ADePT) to help plan the building design process. The core part of ADePT is a dependency structure matrix analysis that can help to order the design tasks into the optimum sequence to minimize the number of iterations within the multi-disciplinary design process. Furthermore, a computer tool, DePlan, has been developed by integrating the strategic nature of ADePT with the operational approach of Last Planner [5]. With a focus on viewing design as the flow of information, an Internet-based framework called the process-parameter-interface model was developed to address the design management issues associated with improving design process scheduling and increasing the efficiency of collaboration [6].

3. DESIGN ITERATIONS

Decisions made in the preceding activities may constrain the design search space in subsequent activities to such an extent that design may be

sub-optimal or even infeasible. Accordingly, some design iteration loops may arise, possibly across a number of activities. Thus, iterations across activities should have a great impact on the ability to arrive at a precise duration estimate of a design project. Figure 1 displays the example of design iterations [7].

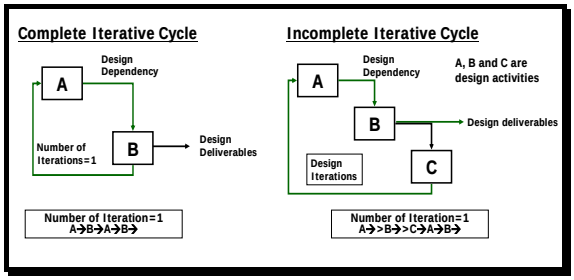


Figure 1. Example of design iterations

The occurrence of design iterations may be due to the following causes:

- Cyclic decision making process. — During designing, decisions often are made iteratively until the design deliverables meet the needs.
- Exchange of design information. — Design information often requires to be exchanged among intra-disciplines, inter-disciplines and multi-disciplines.
- Design review. — Design review always creates design iterations and certain activities may require to be revised to reflect the reviewing comments.
- Design rework. — Design rework produces design iterations because certain activities have to be performed again.
- Design change. — A design change may require extra design deliverables of an activity.
- Non-conformance of clients' requirements — Nonconformance of design deliverables will also produce design iterations. This usually happen in schematic design phase that the project owner selects rejects the proposed alternative. An experienced designer will carefully produce the minimal design deliverables for ensuring that the proposed alternative meets the needs.

4. PROPOSED MODEL

The proposed simulation-based design schedule model consists of four modeling phases (See Figure 2), including representing design process (Phase I), developing simulation network (Phase II), identifying input parameters (Phase III), and selecting output variables and running simulation (Phase IV).

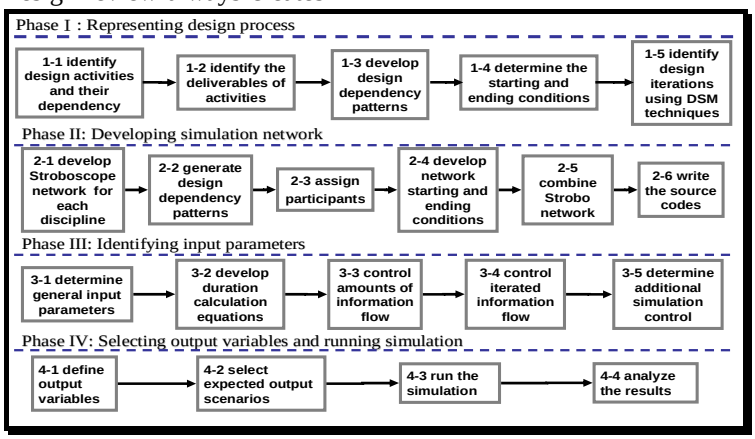


Figure 2. Modeling steps for developing design schedule

4.1 Phase I: representing design process

This phase is to systematically represent the design process of the design work by the following steps: (1) identify design activities and their dependencies, (2) define the deliverables of activities, (3) develop design dependency patterns, (4) determine the starting and ending conditions, and (5) identify design iterations by using dependency structure matrix (DSM) technique.

In this phase, several key points should be noted:

- The design activities discussed herein are end-item oriented or deliverable oriented. That is, the activities are the functional primitive tasks in the operational level. For example, the design activities are such as "preparing floor slab calculations" and "developing floor slab drawings". Conversely, those activities such as "prepare and develop design concept" and "coordinate design concept" are high-level design tasks that do not have definite outputs. And they are not considered in this study.
- Design dependency is the logical relationships between activities. A dependency indicates the information flow carrying with design deliverables.
- In this study, the design deliverables are classified according to the AIA (American Institute of Architects) standard practice and uniform drawing formats.
- Developing the patterns of design dependency

is to facilitate establish a simulation-based network in a modular manner. The patterns can be "serial", "parallel" or "coupled".

- Determining the starting and ending conditions is to identify the major relationships among design disciplines. In a non-process facility building design, the architectural discipline usually leads the design project such that he delivers the plan to other disciplines and receives deliverables from them. Also, for example, 15% completion of floor plan may initiate the start of both ceiling design and finishes design activities; and 25% initiates the start of structural design activity, and 35% initiates the start of mechanical design activity [8]. In the proposed model, the percentage or amount of drawing completion can easily be accessed for initiating the starts of certain designated activities or disciplines.
- Design iterations can across the activities within a single discipline or multiple disciplines. DSM formulation is a matrix that can help represent activity iterations [9].

4.2 Phase II: developing simulation network

This phase is to establish a simulation-based network and write the source codes for the network. A simulation language, Stroboscope [10], is adopted to implement the simulation-relevant algorithms of design scheduling described in the proposed model. Stroboscope often is applied to dynamically access the state of the simulation and the properties of the resources involved in construction operations.

The modeling steps of this phase include: (1) develop Stroboscope network for each discipline, (2) generate design dependency patterns, (3) assign participants (e.g., such as architect, designers, or consultants), (4) develop network starting and ending conditions, (5) combine Stroboscope network of the individual networks, and (6) write the source codes.

Based on the cyclic nature of simulation, the iterative nature of design process can be easily captured. Also by incorporating the productivity rates of the design disciplines into a simulation-based model, expected outcomes of design duration can be calculated for measuring design performance.

In applying Stroboscope to this model, the COMBI nodes are used to represent design activities; QUEUE nodes store design resources (e.g., participants and drawings); and links carry the various types of design information. Other simulation control nodes can be found in Martinez [20].

4.3 Phase III: identifying input parameters

This phase is to identify the input parameters for running the Stroboscope model. Some of the parameters are Stroboscope's system maintained variables or control statements. The steps conducted in this phase include: (1) determine general input parameters, (2) develop duration calculation equations, (3) control amounts of information flow, (4) control iterated information flow, and (5) determine additional simulation control.

The major input parameters are such as the drawing amount, conversion factor, equivalent drawing quantity, unit rate, hour rate, participant breakdown ratio, and participant contribution ratio. Notably, the duration of a design activity includes the time to develop drawings and the time to synthesize the deliverables generated by other iterated activities. Steps (2) ~ (4) are related to the programming of Stroboscope.

4.4 Phase IV: selecting output variables and running simulation

Before running the Stroboscope simulation model, this phase selects the output variables that are required by the model user. The steps include: (1) define output variables, (2) select expected output scenarios, (3) run the simulation, and (4) analyze the results.

5. EXAMPLE DEMONSTRATION

The example project is the design of auxiliary space for a factory building that is located in the Science-based Industrial Park, Hsin-Chu, Taiwan. The project involves architectural, structural, HVAC (mechanical) and electrical disciplines. Figure 3 displays the floor plan of the project. And Figure 4 shows the section of the mechanical room of the project.

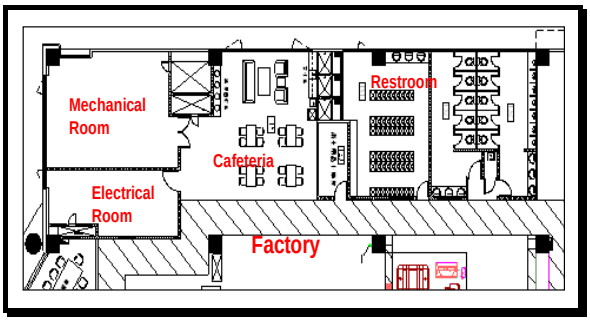


Figure 3. Floor plan of the example project

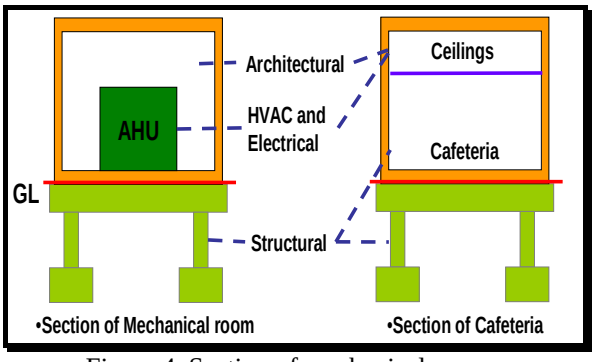


Figure 4. Section of mechanical room

5.1 Evaluations

To evaluate the duration of this design project is based on the modeling steps summarized in Figure 2 and illustrated in Section 4. This section presents some of the major evaluations.

First, the left of Table 1 lists the identified design activities of each discipline for this design project. 31 activities involve in this project. The middle and right of Table 1 display the predecessors and iterated predecessors for each activity.

Then five iterations (iterations A, B, C, D, and E) can be found. Table 2 displays the description of each of the iterations. And Figure 5 presents the partitioned matrix for illustrating the iterations among design activities. Notably, the proposed model still works even without the use of DSM technique. Additionally, Figure 6 further uses a bar chart to represent these iterations.

Table 1. Predecessors and iterated predecessors of each design activity

ID	Activity	Predecessor	Iterated predecessor
A1	**Architectural Design**		
A2	Floor plan design		
A3	Exterior elevations design	A2	A4
A4	Wall sections design	A3	
A5	Ceiling plan design	A3	A30, A24
A6	Restroom details design	A4	
A7	Door and window details design	A6	
A8	Cafeteria furniture design	A4	
A9	Interior elevation design	A6, A5, A8	
A10	Construction details design	A9	
A11	Architectural design review	A10, A7	
A12	**Structural Design**		
A13	Structural calculations	A3	A22
A14	Foundation design	A13	A19
A15	Floor framing design	A14	
A16	Beam details design	A15	
A17	Column details design	A15	
A18	Slab details design	A15	
A19	Structural design review	A16, A17, A18	
A20	**HVAC Design**		
A21	HVAC calculations	A3	
A22	AHU equipment design	A21	
A23	Piping system design	A22	
A24	Air duct plan design	A22	
A25	AHU ductwork details design	A23, A24	
A26	HVAC design review	A25	
A27	**Electrical Design**		
A28	Electrical switchgear calculations	A3	
A29	Electrical switchgear design	A28	
A30	Light fixture and wiring design	A29	A31, A32
A31	Emergency light design	A30	
A32	Smoke detector design	A30	
A33	Emergency exhaust duct design	A30	
A34	Electrical design review	A31, A32, A33	
A35	Design completed	A34, A26, A19, A11	

Table 2. Five identified iterations of the example project

Iteration	Description of iteration
A	Intra-disciplinary design iteration: Wall sections design (A4) will verify the exterior openings size and height. That is, A4 may produce design iterations for exterior elevation design (A3).
B	Multi-disciplinary design iteration: Air duct plan design (A24) and light fixture design (A30) will produce the design information for ceiling plan design (A5).
C	Interdisciplinary design iteration: Assume that the AHU equipment design (A22) produces design iteration for structural calculations (A13) because the designated AHU equipment loading exceeds the structural loading capacity.
D	Intra-disciplinary design iteration: Assume that the structural design review (A19) produces re-design work to foundation design (A14).
E	Intra-disciplinary design iteration: Emergency light design (A31) and smoke detector design (A32) will produce the information for light fixture and wiring design (A30).

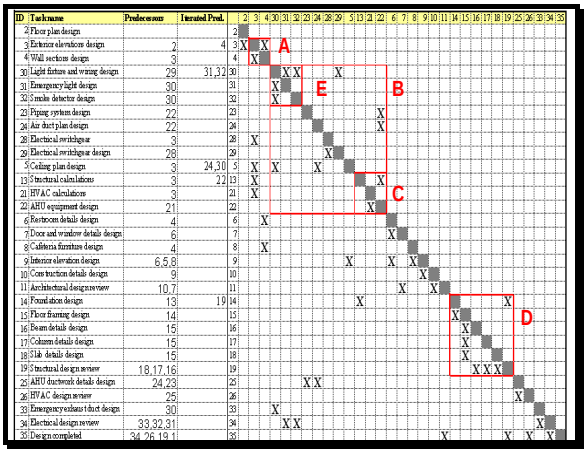


Figure 5. DSM after partitioning

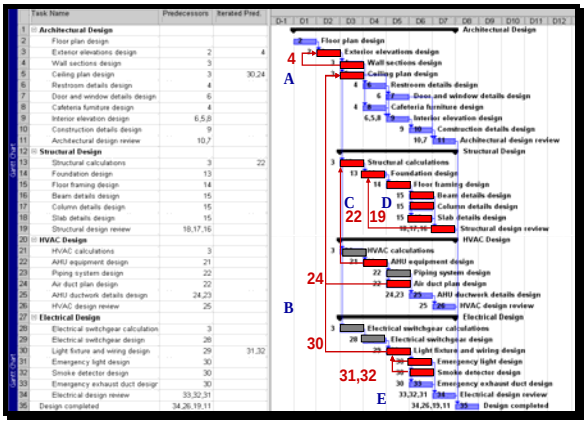


Figure 6. Representation of iterations using bar charts

Finally, a simulation-based network of this design project for this example project can be generated based on the aforementioned modeling phases (See Figure 7). In Figure 7, the integrated network includes all the design activities (represented by COMBI nodes), participants (including architect, designer, assistant designer, structural consultant, and many others), and other simulation control nodes for each discipline. Basically, the architectural discipline starts the work (i.e., activity A2 – floor plan design); and the design work is completed (i.e., activity A35) when all disciplines finish their activities. Notably, this network helps establish a series of programming codes.

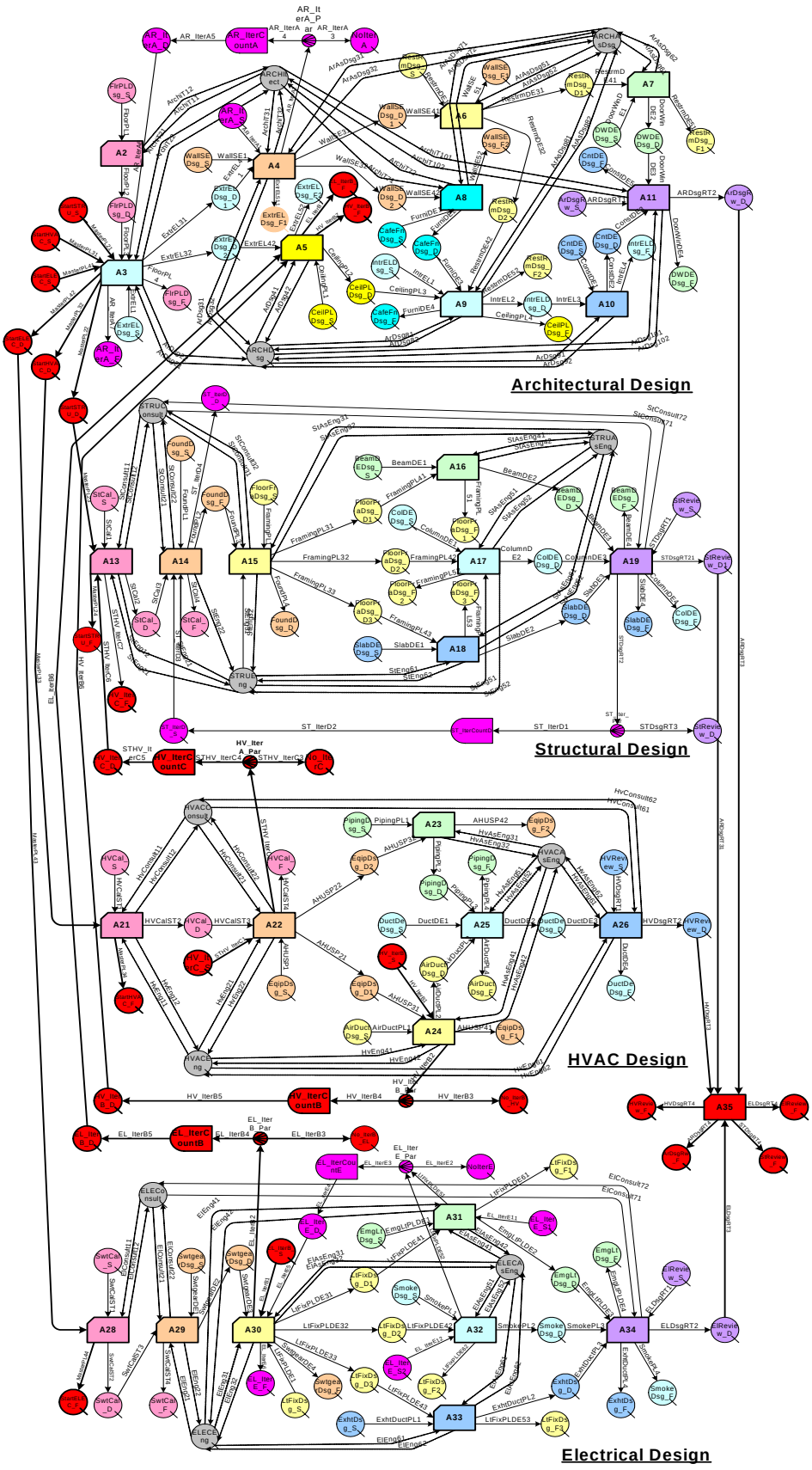


Figure 7. Simulation network of the example project

5.2 Results

After simulation, the total duration of this design project without considering the design iterations equals to 277.55 hours. And the critical path is the architectural and electrical disciplines. Figure 8

presents a summary schedule for this run. When one time of design iteration is considered, the project duration increases to be 326.69 hours. A project design summary schedule is presented in Figure 9.

Another exercise is to find the suitable strategies of allocating the number of design participants by using sensitivity analysis (i.e., performing by different scenarios). For example, four scenarios ((1, 1, 1), (2, 2, 2), (3, 3, 3) and (4, 4, 4)) of different numbers of the architectural participants (architect, designer, assistant designer) are evaluated under the one time of design iteration. The result (Figure 10) shows that the shortest project duration is 224.27 hours for scenarios (3, 3, 3) and (4, 4, 4). Apparently, scenario (3, 3, 3) will be a better choice than scenario (4, 4, 4) that requires higher costs.

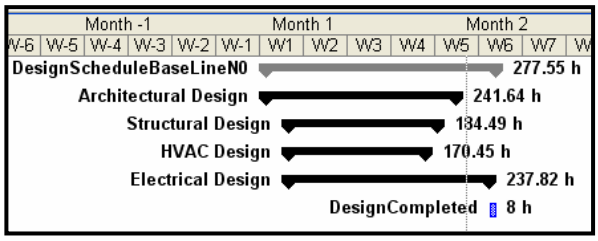
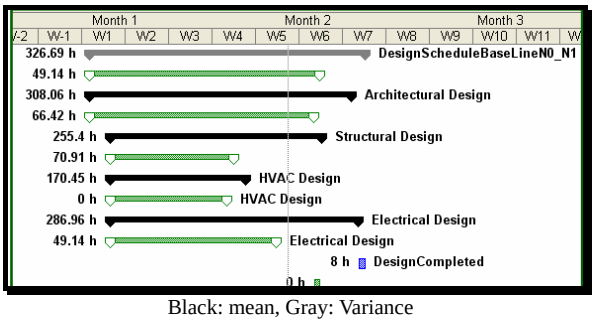


Figure 8. Project summary schedule (no iterations)



Black: mean, Gray: Variance

Figure 9. Project summary schedule (one iteration)

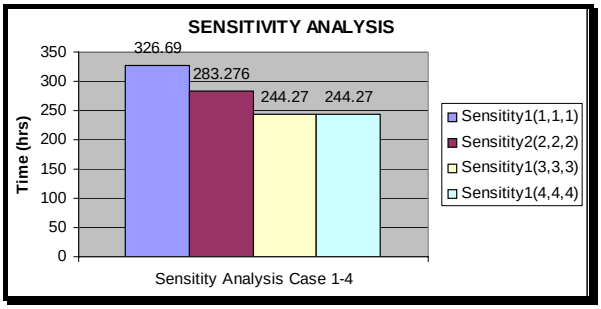


Figure 10. Project durations under different scenarios of architectural participants

6. CONCLUSIONS

While the bar chart and CPM are not suitable to model design schedule, this work innovatively applies the simulation technique to develop design schedule considering design iterations and design resources (such as participants and deliverables). Future research will further address the uncertainties in the model.

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AUTOMATIC DESIGN MECHANISM FOR RESOURCE DISTRIBUTION FOR CONSTRUCTION OPERATIONS SIMULATION

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Abstract: A planner may use simulation for in the analysis and design of construction operation processes to optimize overall performance of a construction system. Normally, the basic elements used in construction operation process simulation system such as CYCLONE (CYCLic Operation NEtworks) are activities and queues. Activity is used to model the execution of the task work which consumes resources and time to perform. Queue acts as a storage location for resources entering an idle state. In the simulation system, queues have to be created according to the ways of assigning resources to activities. Conventionally, planner creates queue at his/her judgment distinguishing what resources and how many should be allocated to which activity. This paper introduces a Genetic Algorithms (GA) based modeling mechanism for facilitating the automation of modeling resource distribution scenarios.

Keywords: GA, simulation, resource distribution.

1. PROBLEM STATEMENT

Computer simulation can be used in the analysis and design of construction operation processes. A planner may use simulation for resource distribution to optimize overall performance of a construction system. Normally, the basic elements used in construction operation process simulation system such as CYCLONE (CYCLic Operation NEtworks) are activities and queues. Activity is used to model the execution of the task work which consumes resources and time to perform. Queue acts as a storage location for resources entering an idle state. In the simulation system, queues have to be created according to the ways of assigning resources to activities. Conventionally, the resources assignment is modeled by planners. Planner creates queue at his/her judgment distinguishing what resources and how many should be allocated to which activity. For instance, suppose three activities (said 1, 2, and 3) have to use resource A. There are five modeling ways to distribute A to those activities. All A can be modeled in one queue meaning the activities share the same pool of A. On the other hand, A may also be distributed to each activity without sharing, and then three queues have to be used in the model. Moreover, any two activities may share the same pool of A and one activity possesses its own A, and therefore two queues need to be drawn. One queue stores the resources shared by two activities and the other provides resource solitarily used by one activity. However, any two activities sharing the same pool of resource may generate different impact on the system performance, thus three different resource distribution scenarios have to be created (i.e., activity 1 and 2, 2 and 3, or 1 and 3 can be modeled for sharing the same pool of A) to see their impact. If the modeled system is complex, the possible resource distribution scenarios could be increased exponentially. This paper introduces a Genetic Algorithms (GA) based modeling mechanism for facilitating the automation of modeling resource distribution scenarios. CYCLONE modeling methodology will be used in the demonstration of this mechanism. In addition, related researches regarding GA-simulation, computer simulation system used for implementing the proposed mechanism, designed mechanism, and case verification are introduced in the following sections.

2. BACKGROUND

The following sections introduce the researches regarding the development of integrating simulation techniques with GA as well as essence of GA. In addition, the computer simulation system COST which was modified for the implementation of the designed mechanism is also presented.

2.1 Related researches for integration of GA and simulation techniques

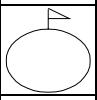
Due to improve the optimization capability, GA has been used in the integration of simulation technique in many areas for facilitating the optimal resource allocation planning. These researches include applying GA-simulation in the optimization of the pastoral dairy farm management [1], shipping and shipyard layout planning [2], the hard disk drive production scheduling [3], and ready-mixed-concrete trucks dispatching management [4]. Moreover, Cheng and Feng [5] integrated GA and simulation in

the development of general purpose simulation system for use in the analysis of construction operations. Similarly, Hegazy and Kassab used GA-simulation technique for resource optimization in construction planning [6]. Though different types of applications of GA-simulation have been proposed, applying GA-simulation for automatically modeling resource distribution scenarios has not clearly pictured.

2.2 CYCLONE methodology and COST program

CYCLONE methodology developed by Halpin [7] is the first simulation system particularly designed for the planning and analysis of construction operation processes. Table 1 presents the basic modeling elements used in CYCLONE and reader may refer to [8] for the details. Since CYCLONE is widely used in the design and analysis for construction operations, several computer simulation systems or programs are developed based on it [5]. Among them, COST (Construction Operations Simulation Tool) was the newly developed one. In COST, the information required to build a CYCLONE model is input through dialogue boxes, as shown in Fig. 1. To explore the details of COST simulation package, readers may refer to Cheng's paper or the user manual of COST [9, 10].

Table 1 Modeling elements used in CYCLONE

Name	Symbol	Function
Normal activity		Units arriving at Normal will be processed right away without delaying.
Combination (COMBI) activity		Units arriving at COMBI will be processed if units are available in all preceding Queue node.
Queue node		Queue provides position that allows units are delayed pending COMBI activities.
Consolidate function node		Consolidate function node performs the consolidate marking.
Counter		Counter measures the modeled system's production rate.
Arcs		Arcs show the logic that units flow from element to element.

2.3 Genetic algorithms (GA)

Genetic Algorithms (GA) is the search algorithm developed by Holland [11], which is based on the mechanics of natural selection and genetics to search through decision space for optimal solutions. The metaphor underlying GA is natural selection. In evolution, the problem that each species faces is to search for beneficial adaptations to the complicated and changing environment. In other words, each species has to change its chromosome combination to survive in the living world. In GA, a string represents a set of decisions (chromosome combination), a potential solution to a problem. Each string is evaluated on its performance with respect to the fitness function (objective function). The ones with better performance (fitness value) are more likely to survive than the ones with worse performance. Then the genetic information is exchanged between strings by crossover and perturbed by mutation. The result is a new generation with (usually) better survival abilities. This process is repeated until the strings in the new generation are identical, or certain termination conditions are met.

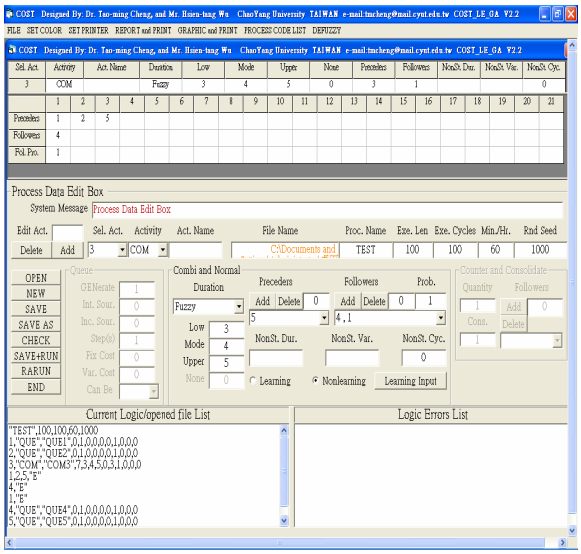


Fig. 1 The input interface of COST computer simulation system

3. DESIGN MECHANISM

The mechanism for automatic design of resource distribution in simulation system is described in two parts. One is the flows of how many queues are created and how resources are assigned in those queues and the other is how GA is integrated. The mechanism of how many queues is created and how resources are assigned in those queues is depicted in Fig. 2.

The integration of GA and the mechanism proposed in Fig. 2 is summarized as shown in Fig. 3. At first, a population of CYCLONE models is generated according to the mechanism depicted in Fig. 2. Secondly, numbers of strings *P(t)* representing models created from first step are evaluated by simulating the CYCLONE models. These strings carry the genetic information of different resource distribution scenarios for the construction operation. Each string's fitness value is decided by simulating the CYCLONE models. The GA then uses the fitness value of each string to determine the probability that the string will be selected in the next generation, the better the fitness value the higher selection probability. GA operators, such as selection, crossover, and mutation, are then applied to the strings to produce the new offspring *C(t)*. The fitness

value of the new offspring is again determined by simulating the CYCLONE models and the genetic operators are also applied to this new offspring. This process is repeated until the termination condition is reached.

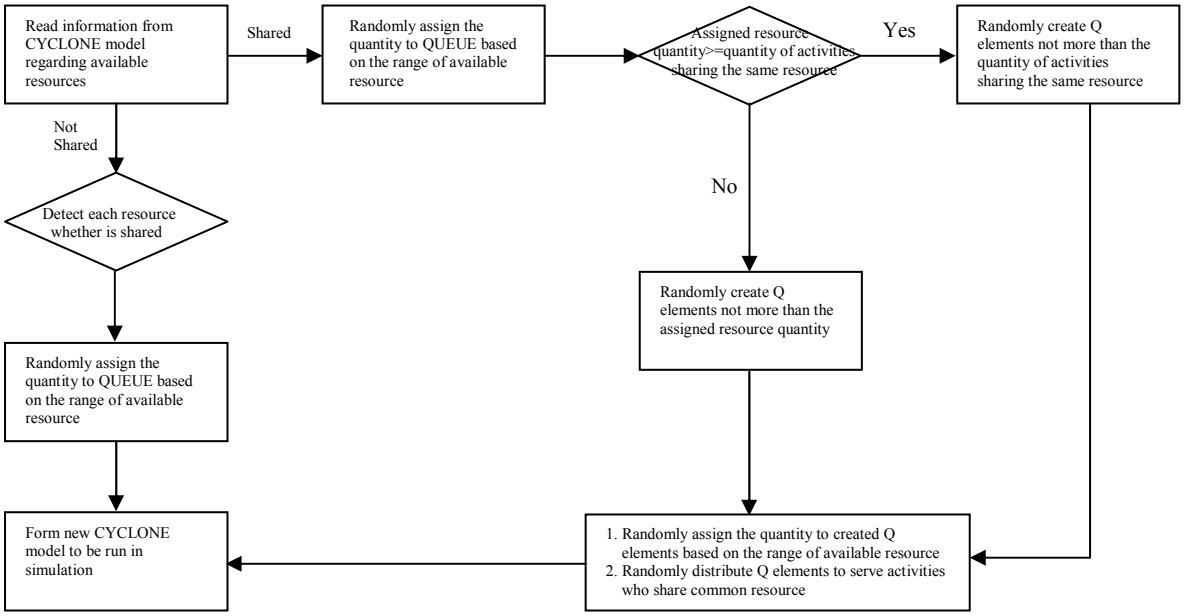


Fig. 2 Flows of forming resource distribution modeling scenarios

```
Procedure Integration of GA for automatic design resource distribution
modeling scenarios
begin
 t ← 0;
 initial p(t) according to the mechanism described in Fig 2;
 evaluate P(t);
 while (not termination condition) do
 begin
  recombine P(t) to yield C(t);
  evaluate C(t);
  select to next population P(t);
  t ← t + 1;
 end
end
```

Fig. 3 A summary of integration GA and proposed mechanism

4. CASE STUDY

The tested CYCLONE model selected from Halpin and Riggs [8] describes the operation of producing the precast concrete elements and is shown in Fig. 4, namely type A model. In this model, concrete is first mixed in a batch plant and poured into precast forms. Then the concrete in the precast forms are steaming cured and moved to a curing tunnel. After being cured, the precast elements are finally transported to storage. In each production cycle, 10 elements will be generated. The resources defined in the model, their initial location, numbers of each resource, and the range of available resource units, together with cost information are given in Table 2. In order to eliminate the influence from uncertainty of activity duration, all activity durations are assumed fixed and given in Table 3.

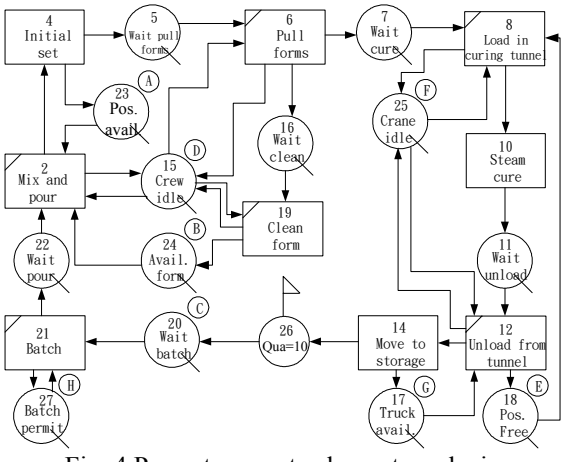


Fig. 4 Precast concrete element producing CYCLONE model (type A model)

As shown in Fig 4, there are two types of resource shared by more than one activity. One is “crew” as indicated by Queue 15 shared by activities 2, 6, and 19. The other is “crane” located in Queue 25 which is shared by activities 8 and 12. There are five and two modeling ways for redistributing resources crew and crane respectively, and together they can form 10 (5*2) different CYCLONE modeling scenarios. For

instance, Fig 5 demonstrates one of the 10 modeling scenarios (type B model). The "crew" resources are separated into two parts in the model. A new created Queue node numbered as 1 represents the crew used for activity 2 only and the other crews in Queue 15 are shared by activities 6 and 19. On the other hand, cranes in Queue 25 still remain being sharing by activities 8 and 12.

Table 2 Available resources and cost information for tested model

Queue node	Resources name	Min. avail. resources	Max. avail. resources	Fixed cost ($)	Variable cost ($/hr)
15	Crew	1	6	150	15
17	Truck	2	6	170	17
18	Pos.	3	12	180	18
20	Batch	10	27	200	20
23	Pos.	3	7	230	23
24	Form	4	9	240	24
25	Crane	1	3	250	25
27	Batch permit	3	4	270	27

Table 3 Duration of activities used in tested model

Element number	Work tasks	Activity duration (Minute)
2	Mix and pour	30
4	Initial set	50
6	Pull forms	20
8	Load in curing tunnel	15
10	Steam cure	120
12	Unload from tunnel	15
14	Move to storage	25
19	Clean form	45
21	Batch	18

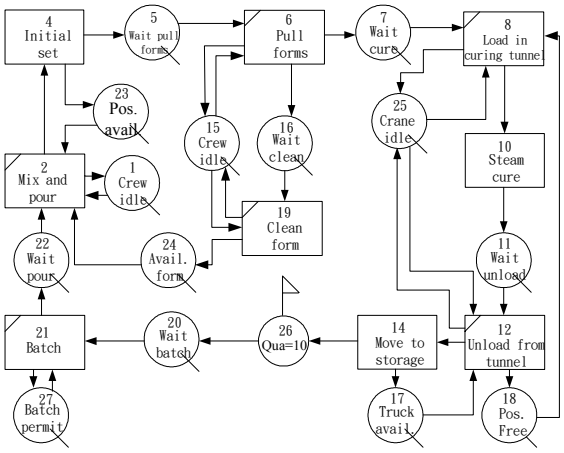


Fig. 5 Type B model for tested example

Table 4 lists all the 10 possible models as well as the ways of distributing the available resources given in Table 2 to those models. The 10 models describe the scenarios that how queues are arranged and what queues are assigned to what activities. In addition, there are 78 scenarios for distributing available resources to 10 models and together with 63,126,000 resource combinations have to be searched for locating the best allocation scenario in order to maximize system performance such as lowering unit cost.

In order to compare the effectiveness of the proposed mechanism, estimating system performance has to be performed in advance. There are two system performance will be tested. One is maximizing system production rate and the other is minimizing system unit cost. As it can be estimated, there are around $6.3*10^7$ resources alternatives, which is not economical to go through the exhaustive enumeration of all resource combinations in terms of computation. As rule of thumb, the more resources are employed, the higher production rate is likely to be reached; therefore, a good guess of the best production rate could be obtained by using the maximum amount of resources for each work task. In addition, to estimate the possible range of production rate of the all resource combinations, the minimum amount of resources for each work task is also tested. The result shown in Table 5 that using type A model for testing indicates that the production rate of using the maximum amount of resources is 27.199 units per hr, which is about 4.4 times of 6.201 cycles per hr by using the minimum amount of resources. In addition, the unit cost of using maximum amount of resources is $606 per unit, which is about 60% of $1001 per section by using the minimum amount of resources.

Table 4 Possible CYCLONE models, resource distribution scenarios, and resource combinations

Type of model	Type of resource distribution scenario	No. of queue node					Possible # of combin.
		15	1	3	25	9	
		Range of available resource					
A	1	1~6	N/A	N/A	1~3	N/A	972,000
B	2	1	1~5	N/A	1~3	N/A	810,000
	3	1~2	1~4	N/A	1~3	N/A	1,296,000
	4	1~3	1~3	N/A	1~3	N/A	1,458,000
	5	1~4	1~2	N/A	1~3	N/A	1,296,000
	6	1~5	1	N/A	1~3	N/A	810,000
C	7	1	1~5	N/A	1~3	N/A	810,000
	8	1~2	1~4	N/A	1~3	N/A	1,296,000
	9	1~3	1~3	N/A	1~3	N/A	1,458,000
	10	1~4	1~2	N/A	1~3	N/A	1,296,000
	11	1~5	1	N/A	1~3	N/A	810,000
D	12	1	1~5	N/A	1~3	N/A	810,000
	13	1~2	1~4	N/A	1~3	N/A	1,296,000
	14	1~3	1~3	N/A	1~3	N/A	1,458,000
	15	1~4	1~2	N/A	1~3	N/A	1,296,000
	16	1~5	1	N/A	1~3	N/A	810,000
E	17	1	1	1~4	1~3	N/A	648,000
	18	1	1~2	1~3	1~3	N/A	972,000
	19	1	1~3	1~2	1~3	N/A	972,000
	20	1	1~4	1	1~3	N/A	648,000
	21	1~2	1	1~3	1~3	N/A	972,000
	22	1~2	1~2	1~2	1~3	N/A	1,296,000
	23	1~2	1~3	1	1~3	N/A	972,000
	24	1~3	1	1~2	1~3	N/A	972,000

Table 4 Possible resource distribution scenarios and resource combinations (continued)

Type of model	Type of resource distribution scenario	No. of queue node					Possible # of combin.
		15	1	3	25	9	
		Range of available resource					
E	25	1~3	1~2	1	1~3	N/A	972,000
	26	1~4	1	1	1~3	N/A	648,000
F	27	1~6	N/A	N/A	1	1~2	648,000
	28	1~6	N/A	N/A	1~2	1	648,000
G	29	1	1~5	N/A	1	1~2	540,000
	30	1	1~5	N/A	1~2	1	540,000
	31	1~2	1~4	N/A	1	1~2	864,000
	32	1~2	1~4	N/A	1~2	1	864,000
	33	1~3	1~3	N/A	1	1~2	972,000
	34	1~3	1~3	N/A	1~2	1	972,000
	35	1~4	1~2	N/A	1	1~2	864,000
	36	1~4	1~2	N/A	1~2	1	864,000
	37	1~5	1	N/A	1	1~2	540,000
	38	1~5	1	N/A	1~2	1	540,000
H	39	1	1~5	N/A	1	1~2	540,000
	40	1	1~5	N/A	1~2	1	540,000
	41	1~2	1~4	N/A	1	1~2	864,000
	42	1~2	1~4	N/A	1~2	1	864,000
	43	1~3	1~3	N/A	1	1~2	972,000
	44	1~3	1~3	N/A	1~2	1	972,000
	45	1~4	1~2	N/A	1	1~2	864,000
	46	1~4	1~2	N/A	1~2	1	864,000
	47	1~5	1	N/A	1	1~2	540,000
	48	1~5	1	N/A	1~2	1	540,000
I	49	1	1~5	N/A	1	1~2	540,000
	50	1	1~5	N/A	1~2	1	540,000
	51	1~2	1~4	N/A	1	1~2	864,000
	52	1~2	1~4	N/A	1~2	1	864,000
	53	1~3	1~3	N/A	1	1~2	972,000
	54	1~3	1~3	N/A	1~2	1	972,000
	55	1~4	1~2	N/A	1	1~2	864,000
	56	1~4	1~2	N/A	1~2	1	864,000
	57	1~5	1	N/A	1	1~2	540,000
	58	1~5	1	N/A	1~2	1	540,000
J	59	1	1	1~4	1	1~2	432,000
	60	1	1	1~4	1~2	1	432,000
	61	1	1~2	1~3	1	1~2	648,000
	62	1	1~2	1~3	1~2	1	648,000
	63	1	1~3	1~2	1	1~2	648,000
	64	1	1~3	1~2	1~2	1	648,000
	65	1	1~4	1	1	1~2	432,000
	66	1	1~4	1	1~2	1	432,000
	67	1~2	1	1~3	1	1~2	648,000
	68	1~2	1	1~3	1~2	1	648,000
	69	1~2	1~2	1~2	1	1~2	864,000
	70	1~2	1~2	1~2	1~2	1	864,000
	71	1~2	1~3	1	1	1~2	648,000
	72	1~2	1~3	1	1~2	1	648,000
	73	1~3	1	1~2	1	1~2	648,000
	74	1~3	1	1~2	1~2	1	648,000
	75	1~3	1~2	1	1	1~2	648,000
	76	1~3	1~2	1	1~2	1	648,000
	77	1~4	1	1	1	1~2	432,000
	78	1~4	1	1	1~2	1	432,000
						total	63,126,000

Table 5. Best guess of both the production rate and unit cost of the tested example

Item	Guess of possible worse result	Guess of possible best result
System production rate	6.201 (units/hr)	27.199 (units/hr)
System unit cost	$1001/unit	$606/unit
Resource combination	Q15(1), Q17(2), Q18(3), Q20(10), Q23(3), Q24(4), Q25(1), Q27(3)	Q15(6), Q17(6), Q18(12), Q20(27), Q23(7), Q24(9), Q25(3), Q27(4)

Higher production rate could be reached by using maximum amount of resource combination; however, it is not clear whether the production rate of the best guess is the highest. Therefore, the example is tested by using the proposed mechanism. However, users only need to choose one of the 10 models as the input model for running simulation. In other word, user does not to input 10 models manually as conventional way.

The input parameters for running GA such as population size, generation number, crossover rate and mutation rate are set to 40, 30, 0.5, and 0.05 respectively according to Cheng's and Feng's suggestion [5]. As a result, the best system production rate and unit cost obtained by running new mechanism are 27.574 cycles per hr and $435 per unit for system production rate and unit cost, respectively (final results shown in Table 6). Compared to the best guess of the production rate, the solution obtained by running the designed mechanism is clearly better. In addition, only 1200 (= 40*30) resource combinations are explored. In other word, only 0.0019% (= 1,200/63,126,000) of possible solution space is explored, and then a better solution with little computation effort is presented. Moreover, the mechanism is implemented via reprogramming COST simulation system and the interface is shown in Fig. 7.

Table 6 Case study testing results

Item	Best system production rate	Best system unit cost
System production rate	27.574 (units/hr)	$435/unit
Resource combination	Q15(2), Q1(4), Q17(6), Q18(12), Q20(22), Q23(5), Q24(9), Q25(3), Q27(4)	Q15(1), Q1(1), Q3(2), Q17(2), Q18(5), Q20(10), Q23(3), Q24(5), Q25(1), Q27(3)
Model Type	Type B as shown in Fig 5	Type E as shown in Fig 6

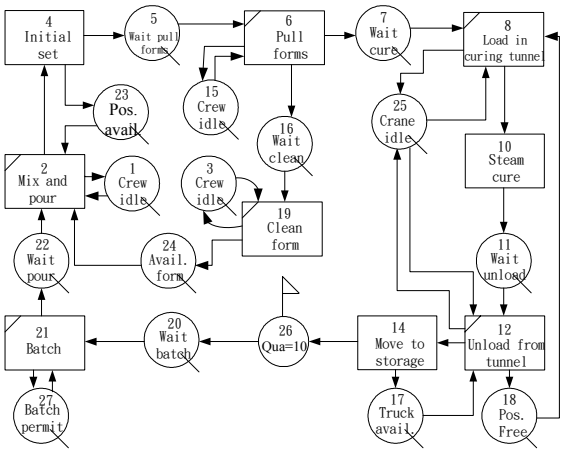


Fig. 6 Type E CYCLONE model for tested example

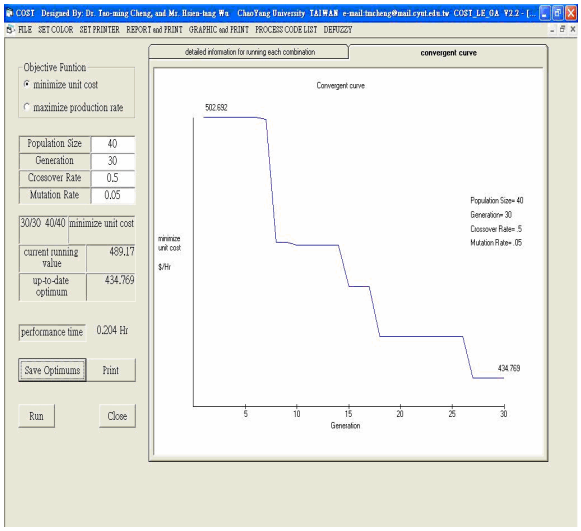


Fig. 7 An interface showing convergent curve while running simulation

5. CONCLUSIONS

Simulation technique is easily used for modeling resource distribution scenarios for construction operations. Conventionally, planner has to create queue elements for storing resources used for activities. If more than one resource distribution modeling ways, user has to input models as many as possible resource distribution scenarios. Moreover, if there are many resource alternatives, it becomes uneconomically for running each resource combination in all models. This research proposes a mechanism that applying GA for facilitating the resource distribution scenario modeling task. The mechanism allows planners input any resource distribution modeling scenario and automatically search the optimal ways for resource allocation. In other word, planners only need to focus on what resource has to be used in what activity rather than worry about drawing possible models describing different resource distribution scenarios. From the case study, the proposed mechanism shows that with little computation and modeling efforts, a better result is obtained for improving system performance.

Acknowledgments

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THE DEVELOPMENT OF REMOTE-CONTROLLED GRAB SYSTEM FOR UNCLEAR ENVIRONMENT

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Abstract: Hydraulic Grabs are capable of placing and removing of underwater structures without hitch by divers. However, grab operators are unable to observe states of the grabs and the objects when the turbidness of water disturbs observation by TV cameras. For this reason, operators still need support and observation of divers during positioning of the grab and grasping the object. Therefore, this paper proposes a remotely controlled system that can support operators by representing the motion of the grab and the shape of the objects using sensor data and VR technology. Two types grab models are developed and experiments are carryed out. The experimental result show the validity of the proposed remotely controlled system for unclear environment.

Keywords: Grab, Remote Control, Grasp Works, VR, Underwater Construction.

1. INTRODUCTION

In 1892-1921, Japanese government of Meiji era constructed The Third Fort in Tokyo Bay for the defense of Tokyo, the capital of Japan. However, it was destroyed by the Great Kanto earthquake of 1923, and now is a reef causing the stranding of ships. The Ministry of Land, Infrastructure and Transport of Japan started the removal of the sunken pieces of The Third Fort from 2000 for the safety of the ships cruising in Tokyo bay.

For the removing work, two hydraulic-powered grabs have been developed. The grabs can lift approximate 40-60 ton weighted load up. The grabs have 4 or 8 claws, power units, and are able to rotate around the yaw axis. Especially, the grabs can perform operate without hitching by divers. However, when the seawater is unclear and TV cameras are useless, the grab operator cannot see the grab or the work objects. Hence the operator requires the instruction of the divers in the water. The divers instruct the operator the position of an object and confirm the grasped object whether in balanced condition or not. Therefore, at each period of the instructions, the divers must stand away from the grab. Consequently, the working efficiency of the grab is declined by this refuge time.

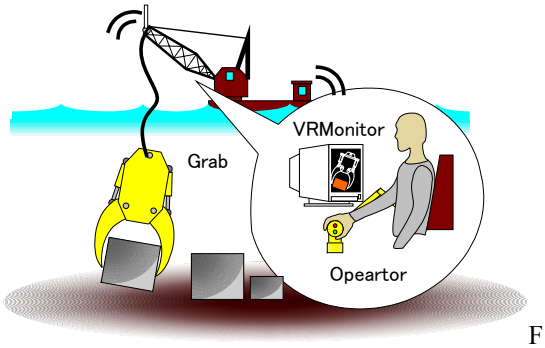


Figure 1. Remote-controlled grab system

To cope with this situation, we are developing a new remotely controlled grasping system that enables an operator to perform grasping works without the instruction of divers [1], [2]. In the developed system, the existing state of grasping works can be represented by CG (Computer Graphics) image drawn on the monitor to give visual information in unclear environment. To represent the grasping work by CG image, the following information is required

(a) Objects states: positions and shapes of the objects

(b) Grab state: attitude, position and angles of joints of the grab

(c) Grasping state: confirmation of grasp and detection of object's slip

In the present grab system, the information of (a) is provided by divers and Echo sound profiling system. We have acquired the information of (b) and (c) by using various sensors and estimation methods, and represented the acquired information on a monitor called "The VR Monitor". Figure 1 shows the image of this system.

To verify the effectiveness of this representation method, we develop two types experimental models of the grab.

This paper describes the remotely controlled grab system that enables an operator to do grasping work in unclear environment, e.g., seawater is unclear , by

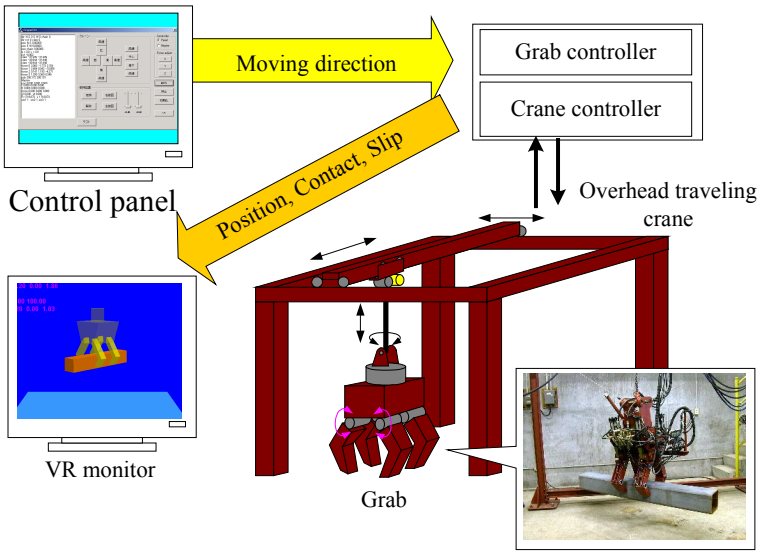


Figure 2. First experimental model

providing visual information based on VR (Virtual Reality) technology and sensors data.

2. THE FIRST EXPERIMENT

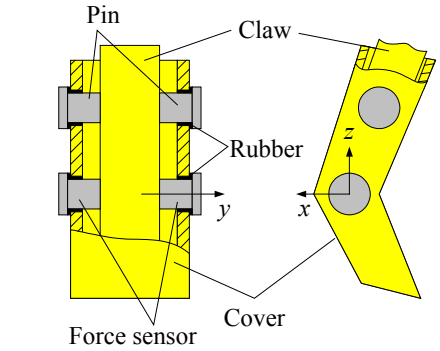
2.1 THE FIRST EXPERIMENT MODEL

The first experimental model of grab shown in Figure 2 is developed to examine basic idea of this remote control system. The developed model has 4 claws and one rotation axis similar to the actual grab. The hydraulic units actuate grab to rotate and grasp an object. This model is able to lift approximate 130kg weighted load up. The grab is capable of 3-dementional positioning by overhead traveling crane. Since the model is suspended by one chain, it is easy to twist and is unstable extremely. To reduce the twisting motion, two tension wires are connected with the garb. Potentiometers measure the angles of joints and rotary-encoders measure the x-y positions of the overhead traveling crane and the fed length of the chain. To obtain more visual information, the grab has contact sensors attached around each claw and slippage sensors mounted on the both sides of the body as shown in Figure 3.

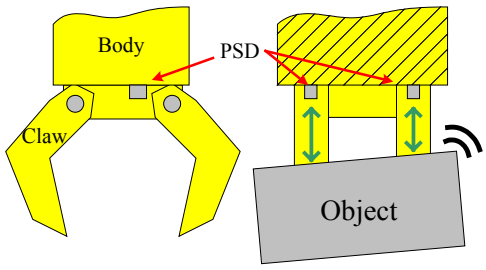
The first grab model has no attitude sensor data, and hence the operator must wait enough time until the swing of the grab stop at its each action.

2.2 GRASPING STATE SENSING

In the filed of robotics, there are many methods have been developed to detect contact and slippage. Most of these methods are for robot hand [3]-[7]. In addition, sensors for such methods are mainly for precision machines, and they are not available under extremely hard conditions such as construction works. Therefore, we have developed new contact sensor and slippage sensor that are able to bear hard conditions.



(a) Contact sensor



(b) Slippage sensor

Figure 3. Sensors to acquiring grasped object state.

(a) CONTACT SENSOR

The contact sensor consists of force sensor units, pin units and claw cover as shown in Figure 3(a). The force sensor units are able to measure the 3-directional forces. The pin units have same frame as the force sensor units. Claw cover is connected with the claw by force sensor units and pin units. When any positions of the claw cover is in contact an object, the contact force acts on force sensor units. By this configuration, the contact sensor is able to detect 3-directional contact and bear the hard condition.

(b) SLIPPAGE SENSOR

Slippage is a change of the distance between the grab and the grasped object. Therefore, the slippage of the object needs to be detected by contact-less distance sensor (Figure 3(b)). PSD (Position Sensitive Detector) sensor is used as a slippage sensor and is attached at the both sides of the grab.

2.3VR Monitor

Grasping work scene is represented on the VR Monitor. The VR Monitor shows the motion of the grab and the shape of targeted objects and ground.

When the grab is in contact with something in the real world, the color of the claw in the CG is changed. In the same way, when the grab grasps and lifts up an object, the CG object is grasped and moved up with the CG grab. When the sensor detects the object slippage, the CG object slips based on the measured distance and then the CG object blinks to inform an operator the slip.

2.4 GRASPING EXPERIMENT

The grasping experiment carried out on ground, in which an operator controls the grab model and removes an object, and places the grasped object on placing site shown in Figure 4. The object is squared steel pipe that weighs approximate 126kg.

This experiment is carried out with three control conditions. The first is direct control by using human eye observation. The second is remote control with VR monitor observation, and the last is remote controlled by using VR monitor observation with initial position error. The position error is enough to cause slippage of the object when the grab grasps and lifts up an object. At each control condition, the operator performs the task five times, and the success rate and work time are evaluated.

From this experiment, it was known that the operator completed the placing operations and accomplished

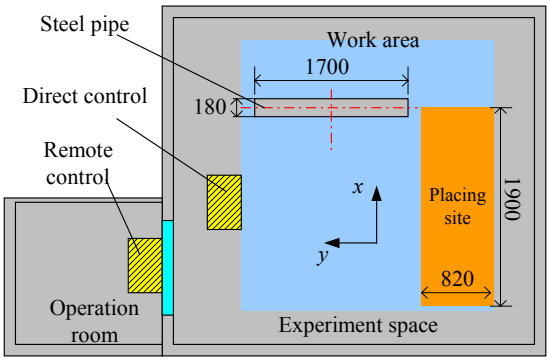


Figure 4. Experimental state.

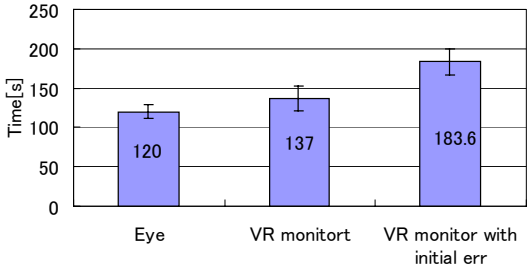


Figure 5. Experimental results of grasping operation

100% success rates irrespective of control conditions. In the case of existing initial position error, the object slipped when the grab lift up the object. In this case, the operator adjusted the grasping position and succeeded the grasping and lifting work again. Experimental results of operation time are shown in Figure 5. The results show that the difference of the operation times between eye and VR monitor observations is very small. It is considered that the grab motion is very slow and furthermore the grab swung at each action, and therefore the operator needs enough time until the grab settle down in any control condition.

Through this experiment, we confirmed that the developed system is effective and useful for the grasping work when seawater is unclear.

3. THE SECOND EXPERIMENT

3.1 THE SECOND EXPERIMENTAL MODEL

Toward to underwater experiment, we have developed the waterproofed type second grab model. This second model has the same mechanical configuration as the first model. This model contains a FOG (Fiber Optical Gyro) attitude sensor that is able to measure the accelerations of 3-axes, angular

velocities and inclinations at roll, pitch and yaw axes. Using this sensor, the second system represents the attitude and dynamical motion of the grab. Three force sensors are mounted on the upper body of the grab to measure the weight and the balance of the load. Contact sensors and slippage sensors are still not installed on the second grab. These will be remodeled from the sensors used for the first grab.

3.2 ATTITUDE REPRESENTATION

One way to represent the grab motion is to move the CG grab by the data of the attitude sensor directly. However, the spatial position of the grab is obtained by the integration of acceleration data. So this method has accumulated error problem. As time passed, the represented spatial position of the grab deviates from the actual position more and more. Note that the operator doesn't require high accuracy of representation to control the grab. Important things are the directions and amplitudes of the swing and the twist of the grab.

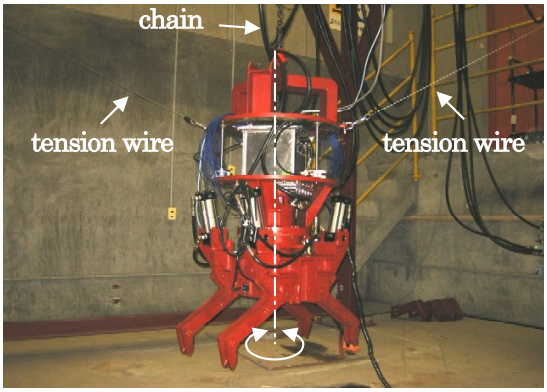


Figure 6. The second model of grab

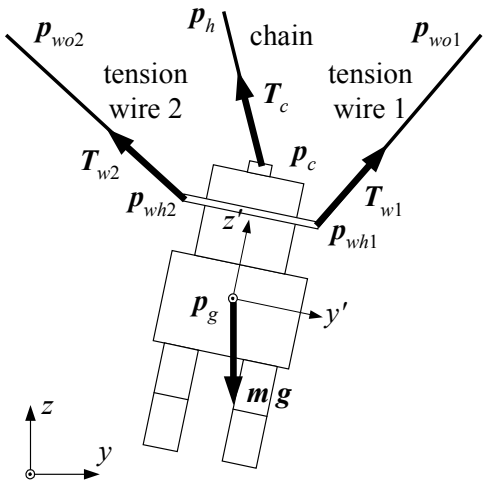


Figure 7. The simulation model of grab

Therefore, the dynamic motion of the grab is represented by the combination of the attitude sensor data and the dynamics model of the grab. The dynamics model is controlled by reference data measured by the attitude sensor. During the grab moves some direction, the dynamics model follows the motion of the grab. And when the grab stops its motion, the state of the grab became stable. In this method, sensor noise, error and drift is reduced or ignored in the motion of the CG grab.

At first sight, the dynamics model is formulated as a simple pendulum, but it is not so simple because the length of the pendulum changes as the fed length of the chain and the base point that is fixed in an ordinary pendulum model is able to move. Furthermore, if the grab touches down the seafloor, the chain is slack, and then the tension of the chain becomes zero. This simulation is not required to represent high precision motion of the grab, and is just required to be processed in real time. Thus, the grab is modeled as one mass system. The constraint by the chain is treated as an external force. The dynamics model of the grab system is shown in Figure 7. The forces exerted on the grab are the tensions of the chain $\boldsymbol{T}_c$, tension wires $\boldsymbol{T}_{w1}$and $\boldsymbol{T}_{w2}$. The dynamical equations of the grab are

$$\left.\begin{aligned} m\ddot{\boldsymbol{p}}_g &= \boldsymbol{T}_c + \boldsymbol{F} + C_v\dot{\boldsymbol{p}}_g + \boldsymbol{F}_c \\ I\ddot{\boldsymbol{\theta}} &= \boldsymbol{\tau} + C_\omega\dot{\boldsymbol{\theta}} + \boldsymbol{\tau}_c \end{aligned}\right\} \qquad (1)$$

where m:mass of the grab, $\boldsymbol{p}_g$:gravity point, $\boldsymbol{F}_c$:control force, C_p:viscosity, I:inertia, $\boldsymbol{\theta}$:inclination, $\boldsymbol{\tau}$:torque, $\boldsymbol{\tau}_c$:control torque, C_w:rotational viscosity. And $\boldsymbol{F}$ is external forces except $\boldsymbol{T}_c$

$$\boldsymbol{F} = m\boldsymbol{g} + \boldsymbol{T}_{w1} + \boldsymbol{T}_{w2} \qquad (2)$$

$\boldsymbol{T}_c$ acts when a distance $\boldsymbol{d}$ from the chain fed point of a hoist $\boldsymbol{p}_h$ to the chain joined point at the grab $\boldsymbol{p}_c$ is equal to or exceeded real length of the chain L_c. $\boldsymbol{T}_c$ is computed as follows:

$$\left.\begin{aligned} T_c &= -\frac{\boldsymbol{d}}{|\boldsymbol{d}|}(|\boldsymbol{F}| + k_c(L_c - |\boldsymbol{d}|) - C_c\dot{\boldsymbol{d}}_c) : \boldsymbol{L}_c \le |\boldsymbol{d}| \\ T_c &= 0 \qquad\qquad\qquad\qquad\qquad : otherwise \\ \boldsymbol{d} &= \boldsymbol{p}_c - \boldsymbol{p}_h \end{aligned}\right\} \qquad (3)$$

where k_c is spring constant. C_c is viscosity that stabilizes tension wire system.

The tension wire i force T_{wi} increases according to the wire fed length L_{wi} and is given by

$$\left.\begin{aligned} \boldsymbol{T}_{wi} &= -k_{wi}\boldsymbol{L}_{wi} - T_{wo}\frac{\boldsymbol{L}_{wi}}{|\boldsymbol{L}_{wi}|} - C_w\dot{\boldsymbol{L}}_{wi} \\ \boldsymbol{L}_{wi} &= \boldsymbol{p}_{wsi} - \boldsymbol{p}_{woi} \end{aligned}\right. \qquad (4)$$

where k_{wi}: spring constant, p_{whi}:wire hooked point at the grab, p_{woi} :origin position of wire, C_w: feeding viscosity. C_w is required to regulate the motion of the grab.

Exerted torque $\boldsymbol{\tau}$ is

$$\boldsymbol{\tau} = \boldsymbol{T}_c \times (\boldsymbol{p}_c - \boldsymbol{p}_g) + \boldsymbol{T}_{w1} \times (\boldsymbol{p}_{wh1} - \boldsymbol{p}_g) + \boldsymbol{T}_{w2} \times (\boldsymbol{p}_{wh2} - \boldsymbol{p}_g) \quad (5)$$

The motion of the dynamics model is modified by the actual attitude sensor data. The controller of dynamics model is PD controller. Translation control force $\boldsymbol{F}_c$ revises error between real acceleration $\boldsymbol{a}_r$ and simulated acceleration

$$\boldsymbol{F}_c = k_{ap}(a_r - \ddot{\boldsymbol{p}}_g) + k_{ad}(\dot{a}_r - \dddot{\boldsymbol{p}}_g) \quad (6)$$

where k_{tp} and k_{td} are control gains of for the translation control.

The rotation control force $\boldsymbol{\tau}_c$ compensate inclination between the real and the virtual coordinate axis of the grab

$$\boldsymbol{\tau}_c = k_{rp}\boldsymbol{t} + k_{rd}\dot{\boldsymbol{t}} \quad (7)$$
$$t = \boldsymbol{i}_r \times \boldsymbol{i}_s + \boldsymbol{j}_r \times \boldsymbol{j}_s$$

where $\boldsymbol{i}_r$ and $\boldsymbol{j}_r$: x and y coordinate axes of the real grab, $\boldsymbol{i}_v$ and $\boldsymbol{j}_v$: x' and y' coordinate axes of the virtual grab, $k_{rp}$and k_{rd}: control gains

The CG grab is drawn on the VR Monitor by the motion of the simulation model. This simulation is calculated by the 4th order Runge-Kutta method at period of 10ms.

3.3 EXPERIMENT OF ATTITUDE REPRESENTATION

To confirm the validity of this representation method, experiment is performed using the second model of grab. The grab moves by time sequenced commands and the data of the attitude sensor are recorded. The time sequenced commands are shown in Table 1. The simulated positions and inclinations are compared with the reference data to confirm the validity of the representation method. The measured position is the point $\boldsymbol{p}_c$ in Figure 7. The reference position of the grab is measured by positioning device consisting of three wire encoders attached at the three corners of the overhead traveling crane frame. The spatial accuracy of the positioning device is approximate ±1cm.

The experimental results of positions and inclinations are shown in Figure 9. The results of x, y position data show that the simulated data are corresponding to the reference data well. In the result of z position,

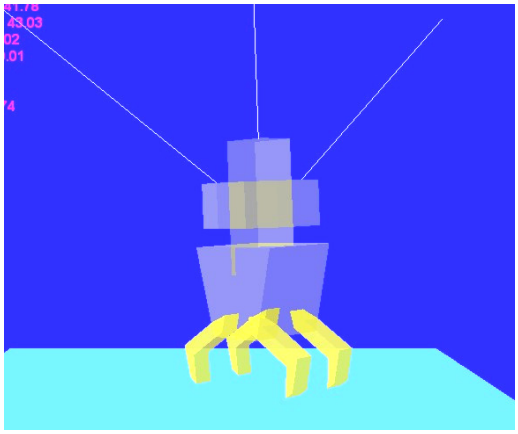


Figure8. Represented CG image of the swinging grab

Table 1. Sequential motion command

Time[sec]	x	y
0	forward	stop
1	stop	forward
2	backward	stop
3	stop	backward
4	stop	stop

the change of simulated the z position is small. This is the reason why the chain of simulated model has spring characteristic shown in equation (3). However, in this simulation, the accuracy of the z direction is enough to observe the motion of the grab. In the results for roll, pitch and yaw inclination angles, the simulated data are corresponding to the reference data well.

As a result, it is clarified that the proposed representation method in this paper is effective to observe the dynamic motion of the grab.

4. CONCLUSION

This remotely controlled grasping systems have the possibility of grasping operation in unclear environment. For practical use of this system, it requires the following subjects:

(1) Waterproofed contact sensor.
(2) Slippage sensor using multiple ultrasonic distance sensors.
(3) Attitude estimation when the grab touch down on seafloor.

As a next step of this study, we have a plan to perform test tank experiment in waves and water current and apply this system to practical grab. By introducing of this remotely controlled grab system,

the safety and the efficiency of underwater construction will be increased.

Acknowledgments

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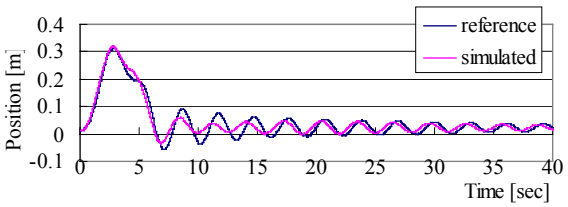
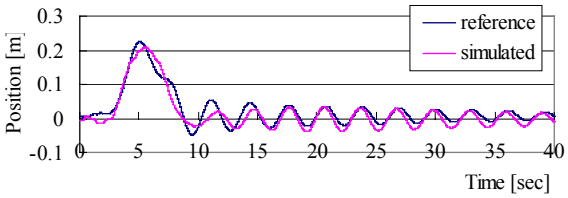
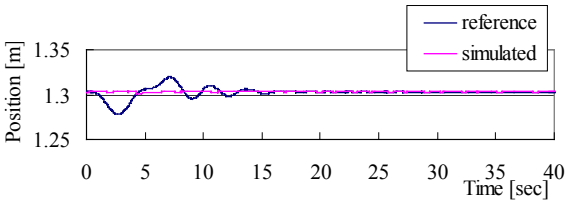


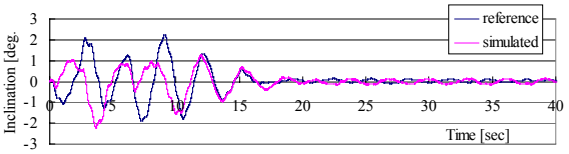
(a) *x* axis



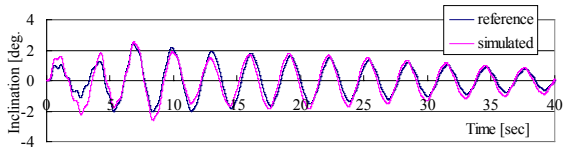
(b) *y* axis



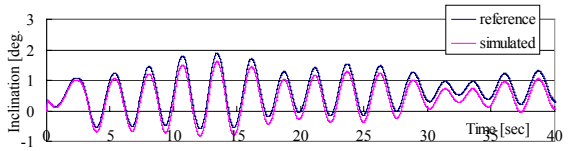
(c) *z* axis



(d) roll



(e) pitch



(f) yaw

Figure 9. Experimental result of the grab attitude

A Study on the Application of VR Technique to Building Construction
Comparisons of Site Photo and VR Image in Construction Progress

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Abstract: Photo taking at an actual job site provides a very useful tool for the record of construction progress and the inspection of built-up members. The photos are also utilized as essential data to carry out the control of construction progress in virtual space. Besides, the situation of construction progress at an actual site might well encounter a conflict with the construction plan that was prepared before the beginning of construction. This invokes the importance of use of site photos in VCS(Virtual Reality Construction Site) that enable the real time construction control by comparing themselves to the images from virtual reality.

In this study the comparison between the site photo taken at an actual job site and the virtual images corresponding to them was carried out to estimate validity of the proposed VCS. Particularly this paper demonstrates the possible troubles during development of a prototype system by acquisition of the site photos from an actual job site.

Keywords: *Virtual reality, 3D progress control, Site photo, Construction planning*

1. Introduction

Due to long-termed economical recession and lack of construction labors in Japan, recent construction activities require not only the improvement of its building skills but also the advanced product control using IT technology to enhance the safety in a job site and the quality of product and reduce the period of construction. To perform the product control properly, useful information such as site photos that provide a valuable means for investigation of ongoing process and quality control in a job site should be well collected and analyzed. This study aims to develop a product control system that is able to compare the VR(Virtual Reality) image simulated in VR space with the site photo taken from a actual job site using Virtual Reality Construction Site (hereinafter VCS), which allows for the time marching control of construction process in VR space prior to actual works in a job site. This paper addresses the comparison between the site photo taken at an actual job site and the virtual images corresponding to them was carried out to estimate validity of the proposed VCS.

2. Comparison of VR Images and Site Photos

2.1 Comparison of two images carrying identical 3-D Coordinate

The site photos taken at various locations at an actual job site are compared with the VR images created with the identical viewpoint and direction vector to the corresponding site photos in virtual space, thereby providing a measure of the control of construction progress and the inspection of built-up members.

Figure 2.1 illustrates an example of VR image

Figure 1.1. construction progress simulation in VCS

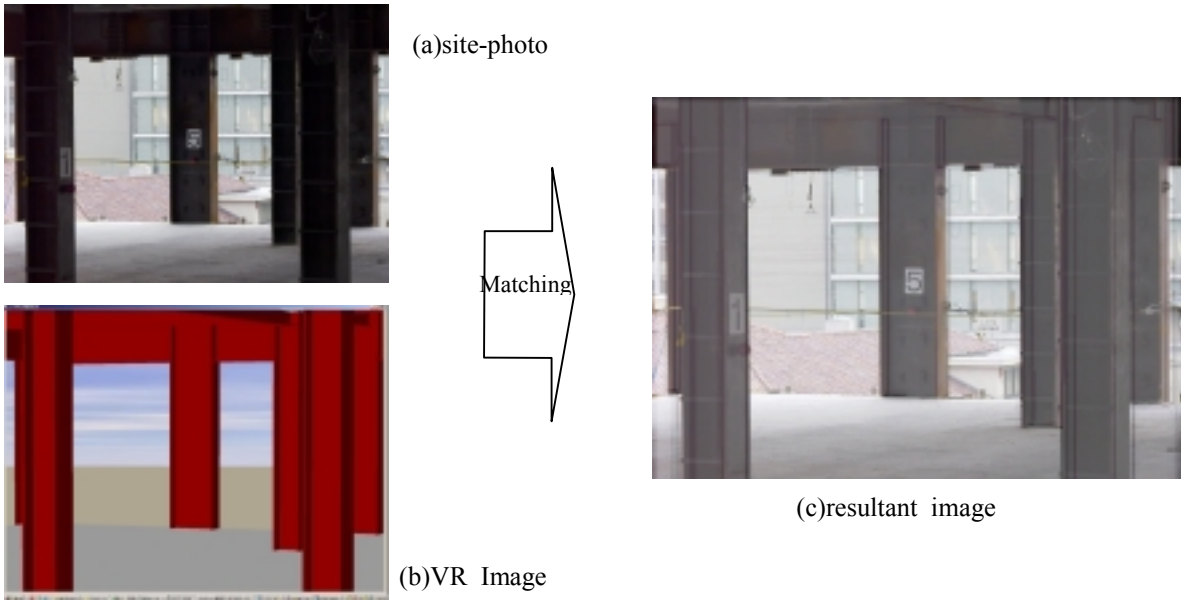


Figure 2.1. Comparison between the real picture and the corresponding virtual image from VCS

matching by the site photo that was taken with the identical viewpoint and direction vector. Besides, Figure 2.1 (c) exhibits a matching of outline from VR image and site photo.

2.2 Data Acquisition from Job Site

2.2.1 Acquisition of Site Photos

Photo taking at an actual job site provides a very useful tool for the record of construction progress and the inspection of built-up members. Besides, the situation of construction progress at an actual site might well encounter a conflict with the construction plan that was readily prepared before the beginning of construction. This invokes the importance of use of site photos for an actual job site that enable the real time construction control by comparing themselves to the images from virtual reality. The site photos for various activities in a job site are taken every day with an accurate coordinates for them which can be suggested by surveying machine. The acquisition of exact coordinate is strongly necessary to correctly match the photos with the images from VCS. Based on the coordinate, the site photos projecting from viewpoint to targeting point can be acquired.

2.2.2 Optical Devices for Acquisition of Site Photos

While taking the site photos at an actual job site, it is strongly required to survey the exact coordinates of selected target for photo taking to make the photos correctly coincide with the images from virtual reality. Non-prism level is used to measure the corresponding coordinates of targets precisely. Figure 2.2 illustrates a non-prism total station equipped with a camera that is able to provide the exact coordinate. The Total Station and camera are both designed to be manipulated by personal computer using remote sensors.

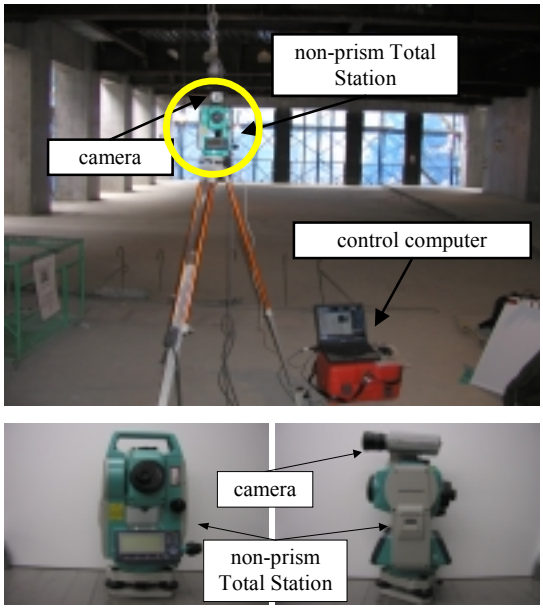


Figure 2.2. camera mounted on Non-prism Total Station

2.3 Correction of Target in Site Photo

While the total station aims a targeting point, the 3 dimensional coordinate of the point can be obtained based upon the angles with respect to the vertical and horizontal axes and the distance between the origin and the point in the rectangular coordinate as shown in Figure 2.3. The following equations can be used to calculate the exact coordinate of the point in the rectangular coordinate.

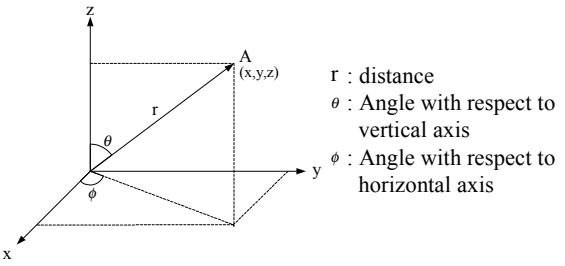


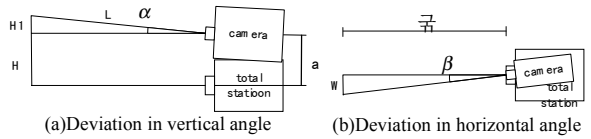
Figure 2.3.Cartesian coordinate

$$x = r\sin\theta\cos\phi$$

$$y = r\sin\theta\sin\phi$$

$$z = r\cos\theta \qquad (1)$$

To match the targeting point in the total station with that in the site photo, the coordinate of point aimed by the total station should be adjusted to exactly coincide with the coordinate at the center of site photo at camera. However, the current arrangement of camera and total station is not able to make a good agreement regarding the targeting direction, since the camera that is mounted on the top of the total station gives the photo with a deviation of coordinate up to 115 mm from that of the surveying machine in Z-axis as shown in Figure 2.4 a. Moreover, this kind of deviation is impossible to be cleared mechanically when the camera is mounted on the top of the surveying machine. Therefore, it is required that those deviations must be correctly measured when the site photos are taken at a job site. And the measured deviations should be corrected to obtain the exact 3-dimensional coordinate of site photo. The deviations can be expressed as α regarding vertical angle and β regarding horizontal angle.



(a)Deviation in vertical angle (b)Deviation in horizontal angle

α : Deviation in vertical angle,
β : Deviation in horizontal angle
a : Deviation due to the mounting location in the vertical axis

Figure 2.4.Deviation in a site photo

By adding the vertical and horizontal deviation to Eqn. (1), Eqn (1) can be rewritten as follows;

$$x' = r\sin(\theta-\alpha)\cos(\phi-\beta)$$

$$y' = r\sin(\theta-\alpha)\sin(\phi-\beta)$$

$$z' = r\cos(\theta-\alpha)+a \qquad (2)$$

3 Searching of Site Photos

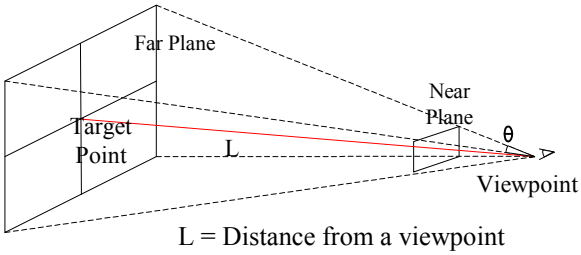
3.1 Necessity of Searching

Using the site photo holding the identical targeting and view point to the corresponding image in VCS facilitates estimation for the situation of site. For the sake of obtaining rather accurate information on the progress of the site, the site photos with a different viewpoint or in the vicinity of the site might be of use. This leads a supervisor to gain the site information more sufficiently. Furthermore, if the site photo with identical targeting point, view point and direction vector to a VR image is not available, these photos can be utilized as an alternative with an appropriate searching to grasp the current situation at the job site

3.2 Scope of Searching in 3-D Space

The view frustum indicates a space domain including all the observable objects in 3-dimensional space. It is like a pyramid of which vertex coincides with the location of camera. The projecting plane forms as a vertical plane with respect to the projecting direction of camera at a distance of L from the camera.

The assignment of a site as an object of monitoring using VCS enable the acquisition of 3-dimensional information on the coordinate and view point of the site. Similarly the 3-dimensional coordinate of a site photo can be also obtained. And each site photo is required to be searched in such a way that the 3-dimensional coordinate of the site assigned as a monitoring object in VCS is allowed to locate inside the 3-dimensional space of the site photo. In other words, the site photos should be searched to hold the target in VCS in the projecting plane.



L = Distance from a viewpoint to targeting point
θ = horizontal angle

Figure 3.1.A view frustum of site photo

3.3 Methodology for Searching

Searching the appropriate site photos for investigation of the site situation out of great number of site photos can provide rather effective use of site photos. The method for searching can be categorized as three according to its purpose. The importance of validity is given to the searched site photos. The feature and purpose of each method are described as follow;

1) Close approach of targeting point in site photo to that in VCS;
provides rather accurate evidence for estimating

the surrounding situations by investigation into them near the targeting point of monitoring object assigned from VCS

2)Close approach of viewpoint in site photo to targeting point in VCS;
provides rather careful examination of targeting point as the distance from the viewpoint to it gets smaller even against the same object

3) Close approach of direction vector of viewpoint in site photo to that in VCS;
enables capture of the targeting point of monitoring object in more realistic sense by utilizing the site photos taken in various directions

4. Validity of Searching

4.1 Valid Range for Searching of Site Photos

It is required to identify the inside coordinate of view frustum to make use of 3-dimensional information from 2-dimensional photo data, which enable employment of multiple information from a photo data. For the sake of it, the distance from the viewpoint to the 3-dimensional coordinate of targeting point, L, and the angle of horizontal view of camera lens, θ, in Figure 3.1 can be utilized. The projection matrix is introduced to figure out the existence of homogeneous coordinate P (P_x, P_y, P_z, 1) [4] within the inside of 3-dimensional space of site photo.

Figure 4.1 shows the distance from viewpoint of camera to targeting point, L, which essentially varies depending upon the type of lens in a camera. In this study, the distance, L, was set up as two times as long as the distance from targeting point.

4.2 Range According to Searching Method

4.2.1 Close approach of targeting point in site photo to that in VCS;

Where the targeting point in site photo approaches to that in VCS, the unit of range is L1, which means the distance from targeting point in site photo to that in VCS. And the validity becomes higher as it reaches to 0. The distance, L1, can be calculated using Eqn. (3). and both the coordinates (Xe,Ye,Ze) of targeting point in VCS and that (Xc,Yc,Zc) in site photo as shown in Figure 4.1.

$$L1 = |\vec{a}| = \sqrt{(Xe-Xc)^2 + (Ye-Yc)^2 + (Ze-Zc)^2} \qquad (3)$$

4.2.2 Close approach of viewpoint in site photo to targeting point in VCS

The perspective of a photo may differ depending upon the location of photo taking, in other words "viewpoint," even it is taken against an identical targeting point. The site photo taken at near targeting point is searched based on the perspective regarding targeting point in VCS. In this case, the unit of range becomes L2, which means the distance from viewpoint in site photo to targeting point in VCS. Besides, D2 indicates range of validity. And the validity becomes higher as L2 reaches to 0. The distance, L2, can be calculated by substituting both the coordinates (Xp,Yp,Zp) of viewpoint in site photo and the coordinate (Xe,Ye,Ze) of targeting point in VCS for Eqn. (4).

$$L2 = |\vec{b}| = \sqrt{(Xe-Xp)^2 + (Ye-Yp)^2 + (Ze-Zp)^2} \qquad (4)$$

4.2.3 Close approach of direction vector of viewpoint in site photo to that in VCS

This kind of searching imposes investigation into the existence of coincidence between the directions of viewpoint in VCS and site photo. The smaller deviation between these two direction vectors indicates that they turn toward almost same direction. The unit of range becomes angle, A1, which usually falls within 90degree because the viewpoint is to turn toward the opposite direction when it overpass 90degree, Since A1 is the angle of reverse view, the smaller value of this can make the validity higher. The vector of reverse view can be calculated from targeting points in VCS and site photo using Eqn. (5), which yields the deviation of vectors carrying two different viewpoints in terms of angle.

$$A1 = c \cdot d = |\vec{c}|\,|\vec{d}|\cos\theta \qquad (5)$$

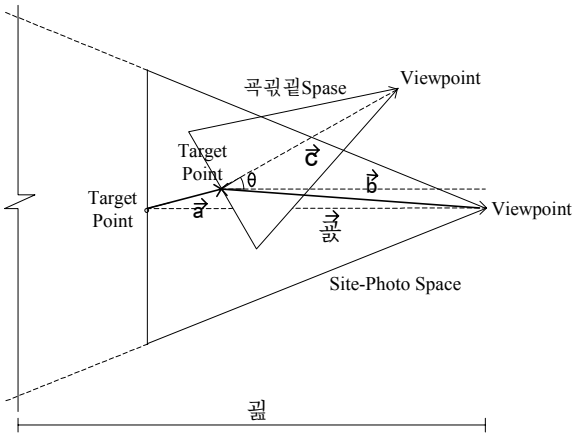


Figure 4.1. 3DS of the VCS and the site-photo which were seen from the top

4.3 Weighted Validity with respect to Searching

In order to perform more efficient searching out of a number of site photos, weight value could be given. Provided that the 3-dimensional coordinate of site selected as a monitoring object in VCS falls within the 3-dimensional space of site photo, namely the subject in a site photo well matches with the monitoring object in VCS, the distance L1, L2 and the angle, A1 calculated for the site photo provide the validity by which weight value is specified. The

weight value ranges between 0~1 for each searching method, so that the maximum weight value for a site photo results in up to 3. Figure 4.1 summarizes the weight values according to each searching method.

Table 4.1. Weight value according to searching method

The searching method	Weight
Distance L1 by the searching method 1	W_1=1-L1/3400mm
	W_1=0 -> L1>3400mm
Distance L2 by the searching method 2	W_2=1-L2/15000mm
	W_2=0 -> L2>15000mm
Angle A1 by the searching method 3	W_3=1-A1/90°
	W_3=0 -> A1>90°
W_0	$W_0=W_1+W_2+W_3$

4.3 Searching Flow

The 3-dimensional coordinate of site selected as a monitoring object is specified in VCS. The viewpoint on the screen of VCS is also defined in terms of 3-dimensional coordinates. Then the appropriate site photos corresponding to selected site in VCS can be searched using those two coordinates. Figure 4.2 illustrates the flow proposed to search the appropriate site photos in this study.

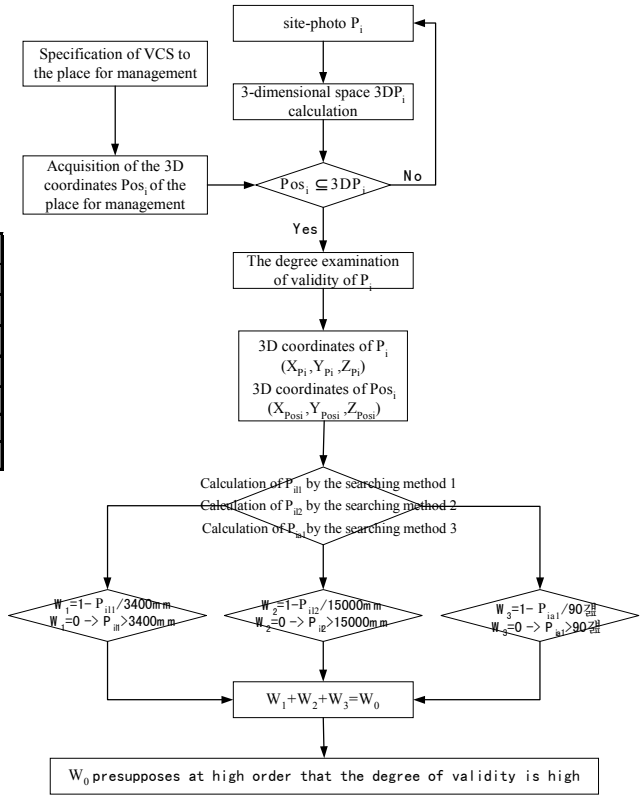


Figure 4.2. searching flow

5. Case Studies

5.1 Adopted Model

Sufficient number of site photos has been taken at 7th floor of new building currently under construction in Nishi Campus of WASEDA University for which 3D modeling of construction process has been established in virtual reality as far as precision is allowed. Comparison between the site photos and the images from virtual space has been also carried out in this study. The precision of modeling has been improved using 3D CAD Micro Station.

5.2 Target for Searching

The site photos were obtained by photo taking at 7th floor of the building under newly construction in Waseda University. At the same time the position of camera and the direction vector for each photo were stored as a set of data in 3-dimensional coordinates. In addition the date and time at the moment of photo taking were also added to the data automatically. Figure 5.1 shows the monitoring objects in this paper that locate within red line in the figure, namely column X8 and YH. And their targeting points has a

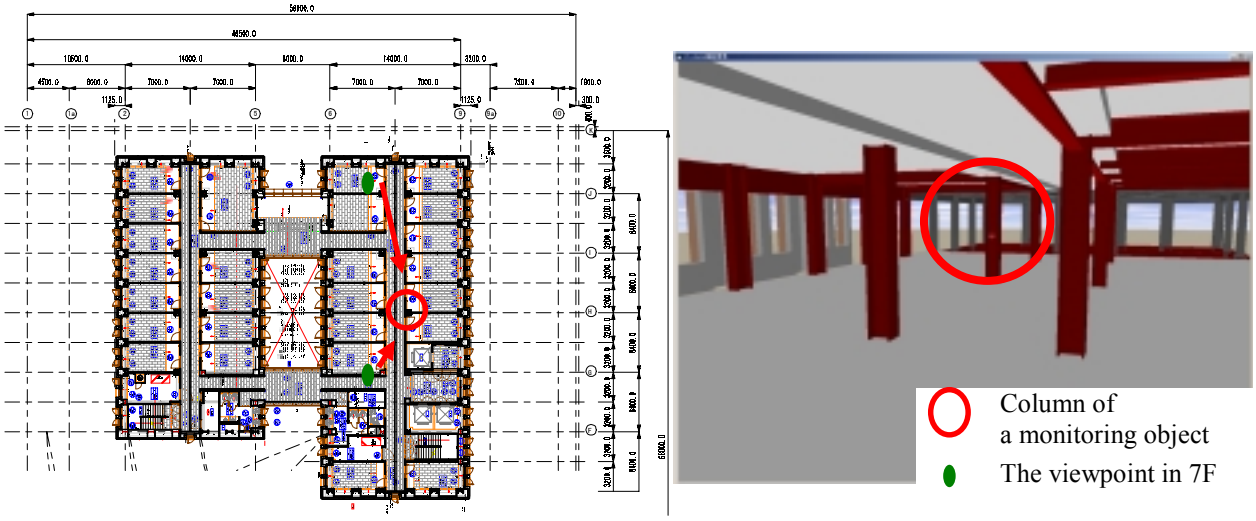


Figure 5.1. Plane view of 7th floor and, VR image for column as a monitoring object

coordinate of x,y,z(40945, 48411, 27546) as summarized in Table 5.1. Figure 5.1 exhibits the 3D VR images of this column corresponding to monitoring object that is acquired from VCS.

Table5.1. 3-D coordinates for monitoring object

monitoring object	7F、Column :X8YH		
	Target Point	Viewpoint	Direction Vector
x	40945	37439	0.31137
y	48411	61384	-0.94198
z	27546	28188	-0.12534

5.3 Results of Searching

4 site photos have been finally searched out from whole 91 site photos. Figure 5.2 shows the coordinates of targeting point, viewpoint and direction vector and resultant weight value for each selected photo simultaneously. Using three kinds of searching methods proposed in this study, the distance, L1, L2 and the angle, A1 corresponding to the site exhibited in Figure 5.2 (a) were calculated as follows; 443mm, 12348mm and 1.5degree respectively. These values yielded the following weight values according to the searching method; for searching method 1, 0.9259, for searching method 2, 0.1784, for searching method 3, 0.9549. The resultant weight value thus came with 2.0617, which is the largest among the values for 4 selected site photos as shown in Figure 5.2. As mentioned above, the most appropriate site photo corresponding to a monitoring object in VCS could be determined automatically in this study. On the other hand, the red circle in Figure 5.2 indicates the column that mainly treated as a monitoring object in this study.

Table 5.2. Final Result of Searching

photo / weight		(a)	(b)	(c)	(d)
W_1		0.9259	0.7023	0	0
W_2		0.1784	0.1784	0.1784	0.1784
W_3		0.9574	0.9462	0.916	0.9138
W_0		2.0617	1.8269	1.0944	1.0922
Target Point	x	40858	40964	40869	40801
	y	48387	48404	41987	42005
	z	27781	26534	27678	26463
View point	x	34226	34226	34226	34226
	y	38655	38655	38655	38655
	z	27959	27959	27959	27959
D-Vector	x	0.39711	0.39427	0.42551	0.35802
	y	0.59538	0.57902	0.52170	0.61973
	z	-0.00751	0.02670	-0.05280	0.02225

6. Conclusion

This paper presents the method of construction planning system using a virtual reality technique which enables the real time construction planning by collecting the information about the actual progress of the job site in the format of photo files and comparing them with the virtual images from VCS. It is successfully proved in this research that comparison between site photos and VR images is valid for the assessment of construction progress in a job site.

Acknowledgments

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(a) (b) (c) (d)

Figure 5.2. Final Result of Searching

INTEGRATED 3D OBJECT TRANSFORMATION AND SIMULATION FOR TOWER CRANE OPERATIONS ON CONSTRUCTION SITES

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Abstract: This paper presents a methodology for integrating 3D (three-dimensional) object transformations with simulation in order to build a 4D model to aid practitioners to visualize tower crane operations on the computer screen. Since the detailed project schedule is already divided into work-packages, the proposed methodology will further divide each work-package in to lift-packages. Each lift-package is geometrically designated for its source and final 3D-geometrical location in space. Additionally, the output of the simulation module will provide the simulated most probable time required to perform each lift. This paper focuses primarily on describing the 3D-geometrical transformation module and its integration with the simulated module.

Keywords: 3D Transformation, Tower Cranes, Simulation, 3D-animation.

1 INTRODUCTION

Tower cranes are the most expensive and frequently-shared resources on commercial building construction sites. Efficient utilization of tower cranes depends greatly on skilled judgments that account for a number of technical and schedule factors. As the number of work tasks and the demand for tower cranes increase, practitioners may require planners to make bold decisions on job conditions for a particular situation, potentially leading to unavoidable mistakes. A poor decision is likely to have significant effects, which will lead to additional costs and potential delays.

Computer simulation proved to be an effective tool for aiding practitioners in modeling complex construction operations. Substantial efforts in the domain of construction have been made after the development of the CYCLONE simulation language [1]. However, the use of simulation as a construction operations planning tool has fallen far below its maximum potential [2]. This unfortunate situation is due in part to the prevalent skepticism among potential practitioners—construction planners and analysts—who are typically well-versed in actual construction operations, to trust the credibility of the simulation analysis. Visualizing simulated construction operations can be of substantial help in communicating the authenticity of simulation analysis to construction decision-makers. In addition, visualization can provide valuable insight into the subtleties of modeled construction operations can thus provide more pragmatic and comprehensible feedback from the simulation analysis to construction personnel as well as to simulation model developers [3].

This paper describes a methodology used to integrate simulation models with the concept of 3D (three-dimensional) object transformations. Objects are moved from their pick location (the material loading zone) by tower cranes to their destination location. Both geometrical locations are known and stored in the lifts database; however, the time needed to move these object is simulated using a priority rating Special Purpose Simulation (SPS) model built in a simulation model called *Simphony* [4]. The SPS model, which assists practitioners to schedule tower crane operations based on the priority rating concept, is described elsewhere ([5] and [6]) and is mentioned briefly in this paper to provide continuity. As illustrated in Figure 1, the proposed integrated methodology has been developed in a 3D Studio environment using a scripting programming language (MaxScript). The output of the simulation model is exported to an ASCII text file. 3D Studio Max is used as a platform for rendering the required frames and animation. The construction of the Natural Resources Engineering Facility (NREF) at the University of Alberta, Edmonton, Alberta, Canada is used as case study to demonstrate the effectiveness of this methodology.

2. SYSTEM COMPONENTS AND ARCHITECTURE

As illustrated in Figure 2, both the priority rating SPS module and the 3D visualization module share the information stored in two objects libraries, designated to 3D tower cranes and 3D project objects (lifts), and three databases comprising tower cranes load charts, site geometry characteristics, and lift packages, respectively.

Figure 3 shows the information dataflow diagram. In order to use the tower crane schedule efficiently, the priority rating SPS module evaluates each work package with respect to the site and tower crane characteristics. The output of the tower crane priority-rating SPS module includes the logic of the simulated lifts sequence and the time required to pick, hoist, and place each lift for a two or three week forecasting period. This output is exported using ASCII text file format for use by the 3D object transformation module, which is built in a 3D Studio environment for rendering and animation purposes. Rendering and animation will provide the user with 4D (3D plus time) short term schedules of two or three weeks worth of forecasted durations. The time limits are a result of the request made by the project manager and also to reduce the simulation module computing time.

3. COMPOSITION OF 3D TRANSFORMATIONS IN TOWER CRANE OPERATIONS

As illustrated in Figure 4, each lift is transformed from an initial location (position S) to a final location (position D), vertically by hoisting the lift up or down, horizontally by moving the trolley along the jib of the crane, and rotationally around the mast of the crane. The crane cycles its operations from one lift in the work-package to another as illustrated in Figure 5. Once all the lifts from a work-package are completed, the crane is expected to move to the next work-package with the highest priority. For each lift or work-package, the simulation module provides the information needed for the 3D-transformation module including the source and destination coordinates and the anticipated travel time, as shown in Figure 6. In this research, the 3D transportation follows the following three-step process:

3.1 Step 1: Hoist the lift from source position (S) to the desired height (S')

As can be seen in Figure 4, **t**his transformation is expressed in Equation (1):

$$S' = T(d_{x1}, d_{y1}, d_{z1}).S = \begin{bmatrix} 1 & 0 & 0 & X_{S'} - X_S \\ 0 & 1 & 0 & Y_{S'} - Y_S \\ 0 & 0 & 1 & Z_{S'} - Z_S \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_S \\ Y_S \\ Z_S \\ 1 \end{bmatrix} = \begin{bmatrix} X_S \\ Y_S \\ Z_{S'} \\ 1 \end{bmatrix} \quad (1)$$

3.2 Step 2: Rotate lift around the mast or z-axis:

This transformation for the angle of rotation θ can be expressed in Equations (2) and (3):

$$\theta = Cos^{-1}\left[\frac{S^2 + D^2 - L^2}{2SD}\right] \quad (2)$$

$$D' = T(d_{x2}, d_{y2}, d_{z2}).S' = \begin{bmatrix} 1 & 0 & 0 & X_{D'} - X_{S'} \\ 0 & 1 & 0 & Y_{D'} - Y_{S'} \\ 0 & 0 & 1 & Z_{D'} - Z_{S'} \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_{S'} \\ Y_{S'} \\ Z_{S'} \\ 1 \end{bmatrix} = \begin{bmatrix} X_{D'} \\ Y_{D'} \\ Z_{D'} \\ 1 \end{bmatrix} \quad (3)$$

3.3 Step 3: Lowering the lift to its final destination from (D') to (D):

Similar to the hoisting of the lift, this step can be expressed in Equation (4):

$$D = T(d_{x3}, d_{y3}, d_{z3}).D' = \begin{bmatrix} 1 & 0 & 0 & X_D - X_{D'} \\ 0 & 1 & 0 & Y_D - Y_{D'} \\ 0 & 0 & 1 & Z_D - Z_{D'} \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_{D'} \\ Y_{D'} \\ Z_{D'} \\ 1 \end{bmatrix} = \begin{bmatrix} X_D \\ Y_D \\ Z_D \\ 1 \end{bmatrix} \quad (4)$$

The composite matrix of the three steps is expressed in Equation (5):

$$T(d_{x1}, d_{y1}, d_{z1}) \times (d_{x2}, d_{y2}, d_{z2}) \times R_Z(\theta) \times T(d_{x3}, d_{y3}, d_{z3}) \quad (5)$$

However, this composite transformation matrix assumes a continuous operation, that is, no time delays. In real life, this assumption is impossible. To accommodate the time delay in the process, let t_1, t_2, t_3 represent the time delays between the three transformations. Equation (5), therefore, can be expressed in the following time-lapsed composition matrix, Equation (6):

$$T(X_1, Y_1, Z_1).t1.T(X_2, Y_2, Z_2).t2.R_Z(\theta).t3.T(X_3, Y_3, Z_3) \quad (6)$$

4. PROPOSED SPECIAL PURPOSE 3D VISUALIZATION SYSTEM FOR TOWER CRANES (SimAnim)

SimAnim has been developed using 3D Studio Max's scripting language, MaxScript, using 3D tranformation concepts of 3D transformations. SimAnim provides practitioners with a powerful tool to animate modeled crane operations with sequential and spatial accuracy in 3D space. SimAnim input data files describe the spatial configuration of modeled systems over a period of time. Since the application is developed inside 3D Studio Max's scripting language, it inherits the strengths of 3D Studio Max. SimAnim is a "post-simulation" visualization application that possesses the following characteristics:

- It uses 3D Studio Max's clock, the speed of which can be controlled by the viewer depending on the desired animation speed.
- Navigation in 3D space is simplified and a desired view can be obtained by controlling the camera using the keyboard or the mouse.
- User can jump ahead or back to any desired location in the simulation by specifying a future or past time-value.
- Animation can be stopped and paused at any time to make static observations in the modeled system.

Simulated operations are visualized in 3D by processing sequential, time-ordered animation data. As shown in Figure 7, the animation data are retrieved from the simulation model in an ASCII text file format. Most of the simulation software is capable of writing custom text output automatically during a simulation run. These include most of the programmable generic and special-purpose simulation languages as well as high-level programming languages. Non-language-based simulation software may also be adapted to generate animation data files during a simulation run. Using an ASCII text file format provides SimAnim with the practical flexibility for use in combination with a wide range of different 3D-CAD models and simulation systems.

5. CASE STUDY

The proposed methodology has been tested in the case of the construction of the Natural Resources Engineering Facilities (NREF) at the University of Alberta, Edmonton, Alberta, Canada. The new building, which will house the Civil and Environmental Engineering Department, is a 28000 m^2 high-rise building consists of nine floors, two underground and seven above-ground level; 700-student classrooms; 78-research labs; and over a hundred offices. The building footprint is 60m by 80; the estimated construction cost of the building shell alone is $56 million (CAN). The building being constructed is based on the design-build fast-track project delivery system, using two tower cranes (as shown in Figure 8). PCL-Max is the general contractor of the project, Cohos Evamy Partners are the design firm, and Stantec is the project consultant. Construction began on February 1st, 2003; substantial performance is expected to commence on October 1st, 2004; and construction is expected to be complete for December 1st.

The many different uses of the tower crane in each stage of construction made simulating the entire tower crane operation very difficult. This study focused on the construction of the second floor (L2) concrete section. The tower crane operations included the lifting of large formwork panels, reinforcing bars and concrete buckets. For these three operations, a simulation model was built in *Simphony* as a SPS template [5] [6]. All related data, including source locations, destination locations, the number of lifts for each work package, hook up and unhook times, and the related distributions of parameters, were defined in the simulation model. The simulation model outputs, which included space- and time-related data, are stored sequentially in ASCII text file format. SimAnim uses this file format to implement the simulation results as a time-scaled 4D model in the 3D Studio Max environment, as illustrated in the screen snap-shots in Figure 8.

6. CONCLUSIONS

This paper presents a 4D-model incorporating a methodology that integrates the simulation models with 3D-transformation and animation tools. The proposed methodology has been implemented into a computer system, utilizing the simulated time and logic for tower crane operations in building construction. The methodology subsequently integrates a 3D transformation concept to simulate the forecasting of construction operations on the screen. The concept of 3D modeling and animation has also increased the efficiency of planners. Once the site is drawn in 3D and the crane and lift are placed, the planner can easily generate any number of views for evaluation and assessment prior to the approval of the plans for execution. In the case study, the client's engineers and safety representatives received a report of the planners' assessments along with nine different 2D and 3D drawings of the lift plan, as well as the 3D animation file displaying the entire crane operation. This information expedites the work of safety officers in order to facilitate the approval of lifting plans. The developed system, SimAnim, provides its users with a powerful, accurate, and instantaneous tool for evaluating and assessing tower crane utilization on construction sites. The case study was used to demonstrate the effectiveness of the developed integrated methodology. The methodology was developed within a 3D Studio Max environment coded in MaxScript language, which ensured the efficient utilization of 3D-object transformation code, as it was incorporated in the software.

Acknowledgments

The authors sincerely thank the organizations participating in this study. The continuous effort and contributions of Mr. Paul Knowles, Project Manager for NREF, are gratefully acknowledged. Special thanks are directed to the NSERC/Alberta Construction Industry Research Chair in Construction Engineering and Management for their technical and financial assistance and to PCL for their unbounded support.

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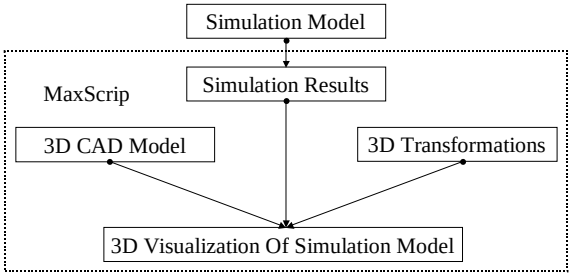

Figure 1: MaxScrip integration components

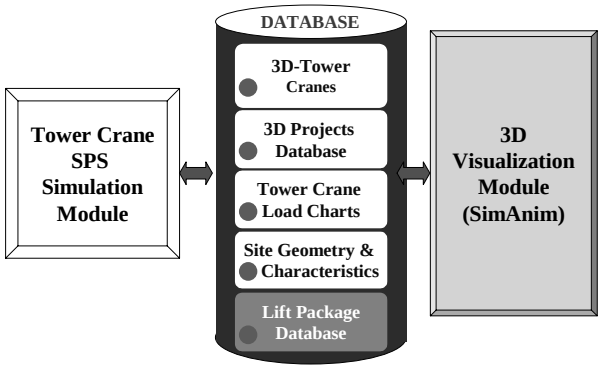

Figure 2: Proposed system components

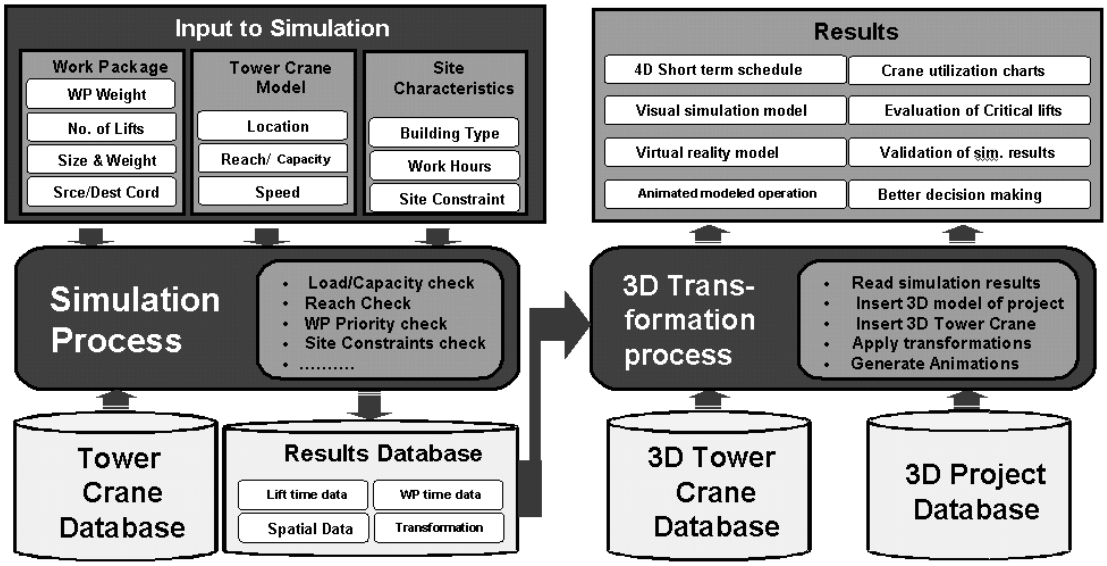

Figure 3: Information data-flow diagram

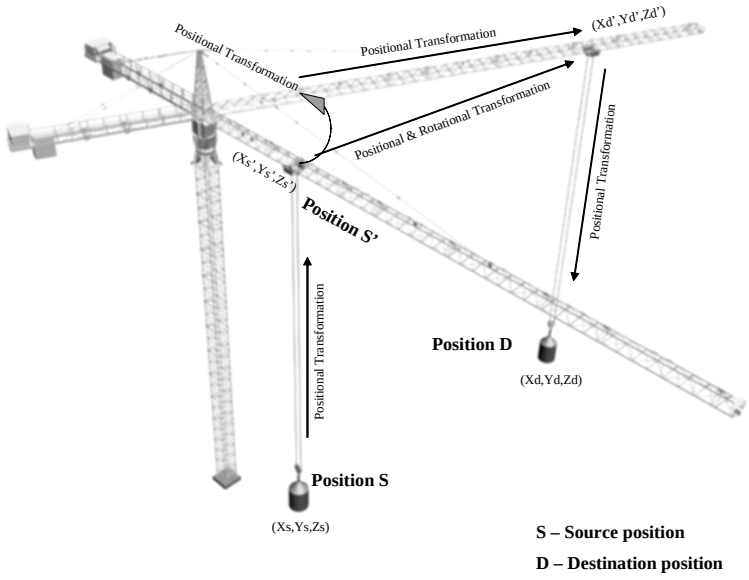

Figure 4: Illustration of objects transformation in space

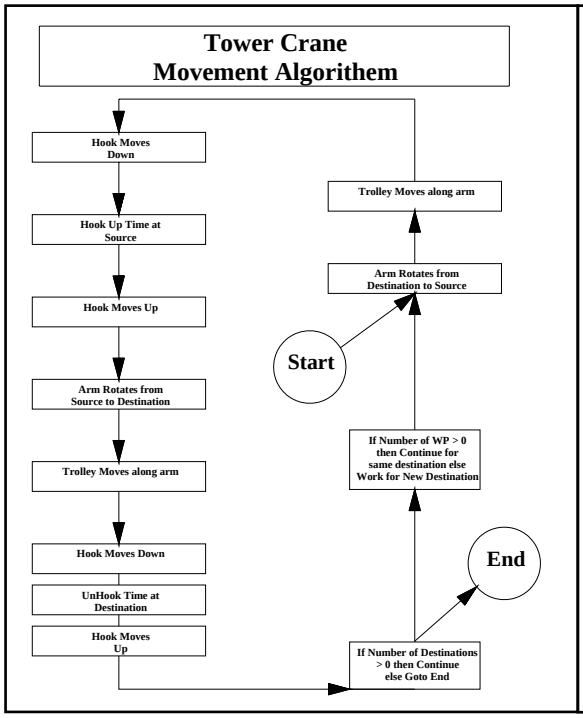

Figure 5: Tower crane cycle

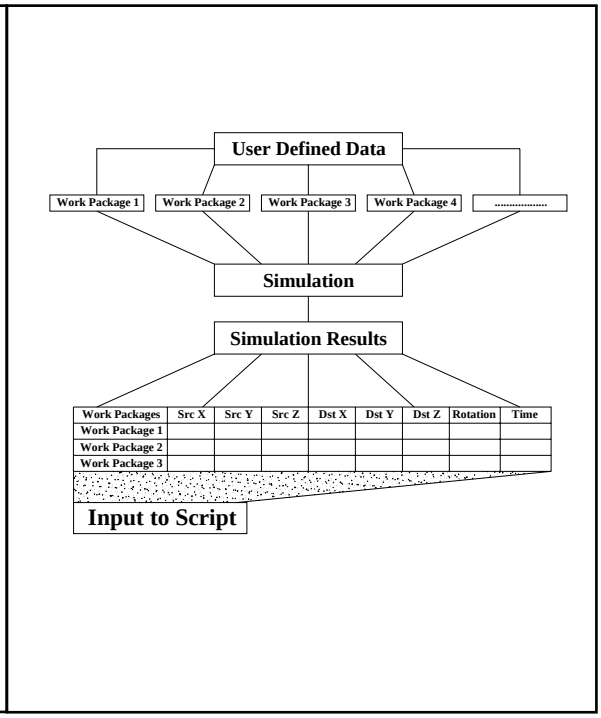

Figure 6: lifts detailed information

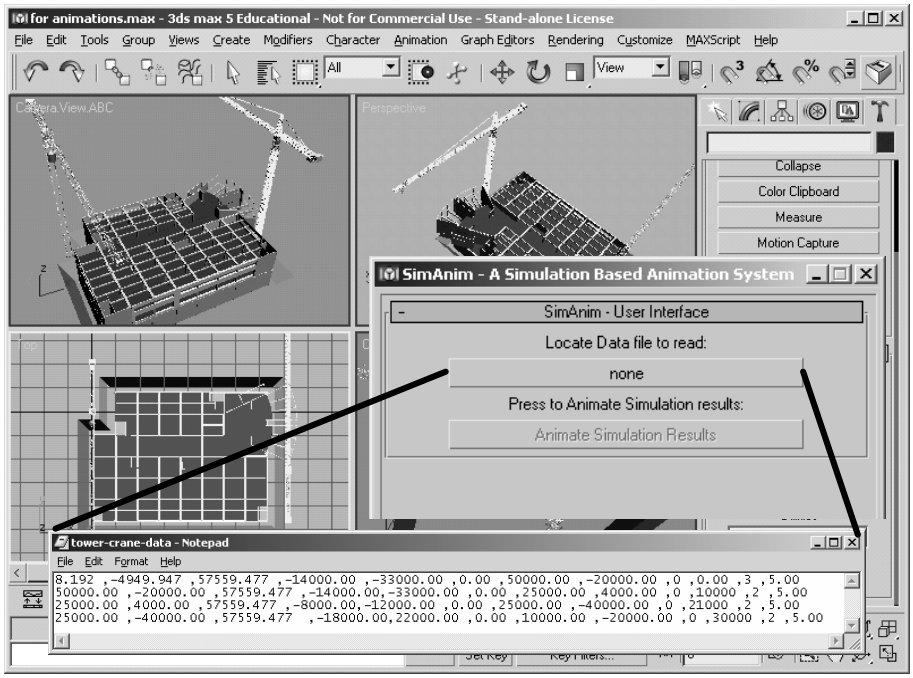

Figure 7: SimAnim process integration

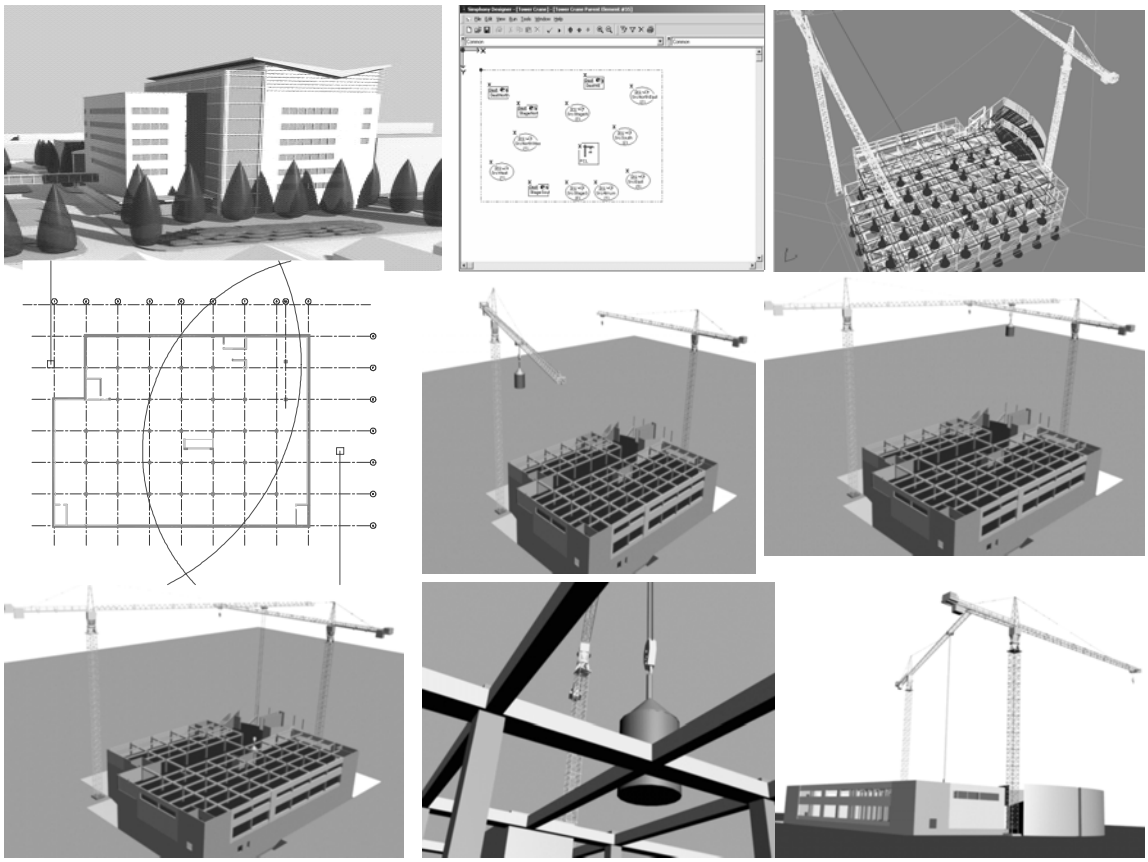

Figure 8: SimAnim screen snapshots of the case study

SIX-SIGMA BASED APPROACH FOR PRODUCTIVITY IMPROVEMENT IN CONSTRUCTION PROJECTS

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Abstract: In order to improve the productivity of construction projects and achieve reliable workflow, it is necessary to quantify the eventual goals for the target process assessment. This research explores the feasible solutions for the construction performance improvement by use of the six-sigma principle, which provides appropriate boundaries of controlling critical sources of the variability. Then, a case study is performed with an aid of a simulation tool toward the end of this paper.

Keywords: performance, six-sigma principle, variation control, buffer size, simulation

1. INTRODUCTION

In the pursuit of the construction productivity, it is important to ensure the quality of work processes and improve the overall performance. There have been a number of construction productivity improvement techniques such as lean production, just-in-time, pull-scheduling, last planner, etc. However, most of the results fell short of our expectations due to the lack of practical techniques in estimating the defect rates of production activities.

In order to estimate the defect rates in reasonably fast and accurate manners, this research introduces the six-sigma principle which is known as the innovative process management strategies at a corporate level in the manufacturing industry. The six-sigma principle may also be applied to construction projects. In construction industry, the use of the six-sigma principle for the performance assessment has started to appear early in 2000. However, the researches so far have been limited to the descriptions of the six-sigma principle and almost no project-oriented construction case study has been reported. This study focuses on the development of the general methodology of using six-sigma principles for construction projects in terms of the productivity improvement and the methodology. This has been verified through a case study.

Many researchers have so far developed various techniques for operation process improvement. Being partly and individually adopted for specific aims, they have been strategically utilized in combination with one another and recently are being designed to realize the innovative lean process. However, the techniques actually place their focuses more on effectiveness in the process of achieving project goals than on efficiency which has been an important issue in traditional production systems. This impedes our full grasp of definite distinction of the newly emerged notion, that is to say, the pursuit of process effectiveness from the existing efficiency-oriented consideration.

Typical construction work is so fragmented that it needs to be performed in accordance with a predetermined schedule. For this reason, the highest priority is placed on the cost and time reduction using resource optimization techniques. It might be difficult to improve the process effectiveness without a substantial performance improvement through ensuring the process efficiency. Furthermore, a reasonable quantitative indicator for the performance improvement is needed to help the field manager set out a definite goal. The performance indicator also motivates field managers for the process improvement.

Since construction projects are not repetitive while manufacturing industry has stable and repetitive processes, it is required to understand the differences in applying the six-sigma principles.

It is noticed that the assembling process is found in both manufacturing and construction work. In this research, an assembling process has been chosen as a sample application to the lowest-level activities and the noticeable findings are presented.

Three phases are presented in this research: (1) strategy and procedure development for applying the six-sigma principle; (2) experimental investigation through the simulation with a real case; and (3) discussions on practical advantages of the six-sigma application to the construction process.

2. THE CONCEPT OF SIX-SIGMA

Recently, customer satisfaction has never been recognized as important as before. High quality (low-defect) products are the key for the customer satisfaction. The corporate-level efforts for maintaining low and stable defect rate become a major issue of the company-wide marketing strategy. The discussion on six-sigma as one of these tools, is vigorously going on in order to meet overall customer satisfaction through achievement of near-perfection in product by using statistical methodologies. The conceptual diagram of six-sigma quality control is presented in Figure 1. If normal value for a process is located at the midpoint between upper and lower limit, each one is 6σ away from the normal value. In short, the range of no defect is $\pm 6\sigma$ from the normal.

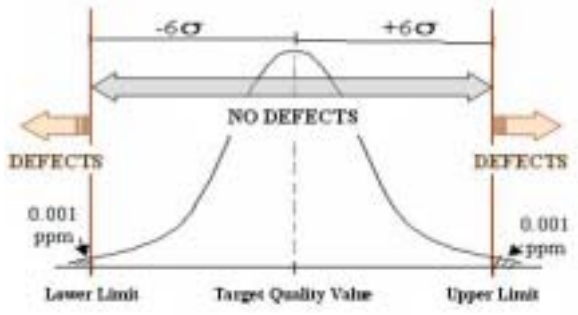


Figure 1. The Concept of Six-sigma

The six-sigma movement is to begin with setting six-sigma quality as a company-wide goal and to implement it through utilizing the necessary tools for reaching it.

The six-sigma movement is to begin with setting six-sigma quality as a company wide goal and to implement it through utilizing the necessary tools for reaching it. The meaning of defect, which was confined just to a product containing a flaw in manufacturing sector, is recently being extended to a variety of industries such as customer dissatisfaction in service industry or accuracy level of documentation in office, and the scope of quality management sigma is also expanding to include not only quality control but also six sigma management (Ahn et al. 2000). Six-sigma initiatives are implemented through DMAIC (Define, Measure, Analysis, Improvement, Control) problem-solving framework in Table 2.

As discussed above, existing (general) methods for improving work processes include many problems in improving productivity of construction projects, but six-sigma, on the other hand, is a statistical approach that enables to set a sigma level as a goal to achieve, and to take action accordingly. To date, construction industry has shortcomings in systemically managing productivity and other performance indicators, and setting the clear objective of improving them, which, in addition, has contributed to limitations to process innovation in the construction site.

Accordingly, in an attempt to overcome these limitations, construction industry needs to utilize six-sigma principles and pursue process innovation systematically and statistically. Due to many large scale projects in construction industry, sophisticated variation management is required in order to ensure conformance to project requirements including safety, quality and duration. Therefore, six-sigma, the objective data-based and statistical methodology, can show greater effects on management of such main indicators in construction than other industries.

Table 1. DMAIC Framework

Phase steps	Step description	Associated tools and techniques
Define	What problem needs to be solved?	Process mapping, brainstorming
Measure	What is the problem? What is the current performance?	Pareto chart, control chart, process sigma calculation
Analyze	When, where and why do defects occur?	Cause and effect diagram, benchmarking
Improve	How can the problem be solved?	Regression analysis, multi-variable chart, cost analysis
Control	How the sustainable quality improvement can be done?	Institutionalization of the improved process Process monitoring for continuous process improvement

3. STRATEGY FOR SIX-SIGMA IMPLEMENTATION

Different from manufacturing industry, fragmented and project-oriented work processes are unique to construction industry. For successful application of six-sigma, construction industry needs its own strategy for successful implementation of six-sigma.

3.1 Integration of six-sigma and other innovative methodologies

For successful application of six-sigma, construction industry needs to clearly define strong and weak points of existing techniques for process innovation. It is necessary to maintain their advantages, which make the established infrastructure and strategies reused, and to overcome limitations through employing new concepts. Steel Case, Co., U.S.-based company, achieved improvements in cost, quality, and time reduction in cost and through incorporating lean manufacturing system and statistical tools for improvement in manufacturing process (Steel Case Corp., 2002). In addition, Kroslid(2001) concluded that integration of both lean and six-sigma can result in better performance. Kroslid also emphasized integration of lean manufacturing system and six-sigma principles including implementation steps (DMAIC) through case study. Lean construction, therefore, can show better accomplishment when combined with six-sigma concepts.

3.2 Phased application of six-sigma

Unlike the manufacturing process, many construction activities are being done at large open land. In addition, they have more uncertainties in spite of repetitiveness in work process. Therefore, it is important to select the work process similar to a manufacturing process which is usually sensible enough to reflect the impact from adjustment of process orders, resource level, etc. Prudent and systemized approach is required in selecting an activity applied to six-sigma concepts.

This research suggests two steps to the phased application of six-sigma. The first one of two steps deals with processes similar to ones of manufacture such as assembling works which are main parts of the plant construction or the equipment installation projects. The second step includes more complicated construction process than process similar to manufacture's. Second step needs a discreet and careful attitude in applying six-sigma.

Performance measurement system is one of the most important support systems for deploying six-sigma concepts through construction processes. Prior to adopting six-sigma, construction companies should design their own basic strategies and policies in consideration of their conditions.

In determining the performance indicators for six-sigma application, it is required to consider the distinction between not only those of each process but also key factors critical to project success for each construction phase. At this time, six-sigma methodologies are aiming at the broad process improvement and are required to select the process related to the subject CTQ in order to avoid interrupting the continuous effect of process improvement not only those of each process but also key factors critical to project success for each construction phase. At this time, six-sigma methodologies are aiming at the broad process improvement and are required to select the process related to the subject CTQ in order to avoid interrupting the continuous effect of process improvement.

CTQ (Critical Total Quality) means the key quality-influencing element and the most related element to a process performance indicator in fact. For instance, if productivity is used as its performance indicator, the reliability of resource flow can be set as a main CTQ due to the closest association with productivity. Generally, the mean and standard deviation of collected data are calculated, and then the present sigma level of the process is measured according to the defined performance standard after determination of process capability index C_P with assumption of no skewness in data.

$$C_p(\textit{process capability index}) = \frac{USL - MEAN}{3 \times STDEV}$$

$$\textit{If only USL given}, \quad \sigma(\textit{sigma level}) = 3 \times C_p$$

where USL: upper specification limit

Mean: the mean of the data

STDEV: the standard deviation of the data

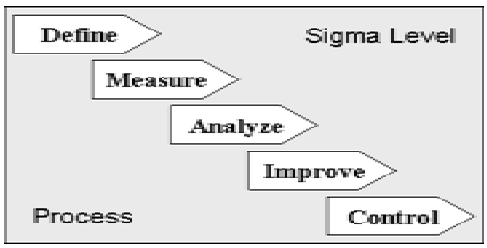
3.3 Basic Framework for the Six-sigma-based Management

The six-sigma concept can be appropriately employed to the construction process control within the basic framework, as shown in Table 2, which is developed upon the previous fundamental researches. Closely associated with the existing techniques for the manufacturing process improvement, the six-sigma-based management is applied in construction projects according to the strategies as depicted in the preceding sections. We repeat the consecutively organized steps of defining, measuring, analyzing and adjusting the input values so as to enhance the indices of process performance quality by continuously monitoring the outcomes and identifying potential problem areas.

Considering the highly uncertain attributes immanent in construction processes, it is not so a practical way that the six-sigma level is strictly adopted for all cases when we control the variability of the above-specified factors directly linked to process performance within a fixed narrow range. Provided

with quantitative goals by the degree of the sigma level, therefore, proceeding with relevant efforts of process assessment and management, as such, need to be more emphasized than attaining the six-sigma quality. On the other hand, to describe important topics we consider last but not least when the general six-sigma application procedure, DMAIC, is imported into the construction process management, its special characteristics different from other industries should be fully incorporated at each phase.

Table 2. Basic Framework for the Six-sigma Application to Construction Projects

Indicators influencing on process performance (input)	Six-sigma application procedure (DMAIC)	Indices of performance improvement (output)
Material quality		Cycle time reduction
Safety measures		Efficiency improvement
Buffer size		
Idle time of labor		Productivity improvement
Idle time of equipment		
Variations in cycle time	Improvement achieved through minimizing waste and establishing quantitative targets based on the six-sigma application strategy	Increased amount of works
Earned value achieved		Buffer size optimization

4. CASE STUDY: Iron-reinforced-bar Assembling Process

To demonstrate the advantages of the six-sigma-based management strategy suggested in the previous section, we targeted an assembly work at the lowest level of an entire construction process and did comparative analyses of its performance improvement with an aid of a simulation tool. Among the power line construction was an iron-reinforced-bar assembling process selected for the case study, and EXTEND^{TM}+BPR was employed to develop the simulation models.

4.1 Definition of CTQ

In this case, productivity improvement level was set as the principal indices of process performance quality to begin with. Then, we identified the factor which is most closely linked with productivity by observing process variations. Through a repeated analyses with various independent variables, the degree of variations in work process cycle time was found to be as CTQ.

Subsequently, it was needed to determine the target CTQ in order to evaluate the current process status and establish the improvement goal. Figure 2 displays the cycle time variations for a relatively long period of the assembly works. Reasonably guessing from this distribution with some extraneous points taken into account, we fixed 40 minutes as the target CTQ to achieve a desirable productivity.

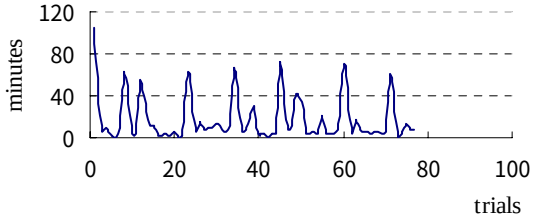


Figure 2. Cycle Time Variations

Based on the target CTQ, we found from the equations (1) and (2) that the current defect rate which assumes the possibility of cycle time over 40 minutes was represented as 1.41-sigma level. This is yet far below the six-sigma level, thus it is required to set up the strategies to improve work flows and accordingly enhance the process reliability.

$$C_p = \frac{USL - MEAN}{3 \times STDEV} = \frac{40 - 17.46}{3 \times 16} = 0.47 \qquad (1)$$

$$\sigma = 3 \times C_p = 1.41 \qquad (2)$$

On the other hand, further analyses revealed the buffer size had the most critical influence on the assembly work cycle time. Therefore, through the buffer size optimization we improve the sigma level in CTQ and make progress in the entire process performance.

4.2 Improvement of CTQ

The improvement has achieved in two phases: (1) the improvement by the modification of the assembling process; (2) the improvement by the resource buffer size optimization.

Before the process modification and resource optimization, the resource level was 8.4, and sigma level was 1.41. After the process modification (Column 1 and 2 of Table 3) productivity has improved by 0.003 while sigma level reached only 1.72, which is not a sufficient improvement both in terms of productivity and sigma level.

After the buffer size optimization, the targeted result (six-sigma level) has been obtained. By increasing the buffer size from 11.5, 14.5, and 19.2, the productivity has improved to 0.055, 0.06 and 0.061, respectively. Sigma level has also improved as high as 6 when the buffer size is 19.2. However, the productivity has risen by only 0.001 by adding 4.7 resource unit and 1700 cost unit.

Therefore, it is suggested that 14.5 is the most economic buffer size, maintaining reasonable productivity and sigma level.

Table 3. Performance Index by Buffer Size

Item	Buffer Size (ton)				
	8.4	8.4	11.5	14.5	19.2
Productivity (ton/min)	0.049	0.052	0.055	0.06	0.061
Total Cost (\10,000)	940	980	1220	1,440	1,610
Additional Cost (\10,000)	350	350	550	720	885
Throughput (ton)	236	252	268	288	290
Cycle Time (min)	162	150	154	159	160
Cycle Time Sigma Level	1.41	1.72	2.58	3.64	6

4.3 Result Analysis

According to the simulation results that depicted fluctuations in the sigma level, the process reliability in terms of variations in the various performance indices can be evaluated in the midst of productivity-cost tradeoff relationships and about 20 tons of the total material stock is required to last during the targeted assembling work period in order that the process cycle time should not lapse into excessive volatility which assumes the defect rate of not reaching the degree of the six-sigma level. However, there exist spatial limitations to the sufficient inventory status and furthermore the maintenance cost escalates as the storage volume grows, thus it is recommended that we regulate the storage between 14.5 and 19.2 tons so as to have the work efficiency remain as high as the process reliability is attained to a satisfactory level.

The graph that describes the relationship of the sigma level in CTQ and productivity appears in Figure 3. We can find out the productivity gradually improves while the cycle time variation ranges are getting narrower from the 40-minute width which was set as a standard performance measuring criterion and it is also observed that around the 4 sigma level the improvement comes to its upper limit achievable through the control of variability in CTQ.

To confirm this phenomenon from a different point of view, Figure 4 suggests the simulated plotting of the material storage-productivity relationship, which takes on almost the same curved shape as that in Figure 3.

On the other hand, Figure 5 graphically shows the linear incremental relationship between the storage and the cost. This trend being compared with the previous results as to the process efficiency improving aspects, it is necessary to assess the optimum inventory level where we can expect a desirable productivity at a reasonable expense.

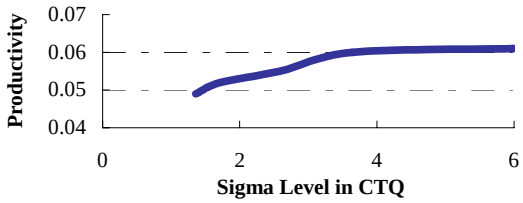


Figure 3. Relationship between Sigma Level in CTQ and Productivity

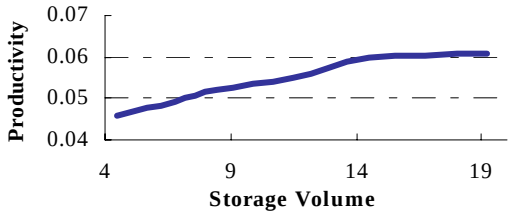


Figure 4. Relationship between Storage Volume and Productivity

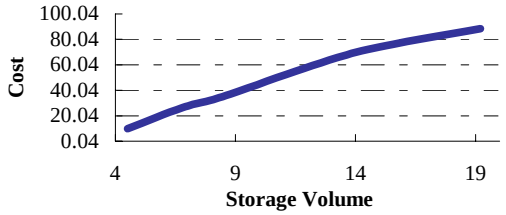


Figure 5. Relationship between Storage Volume and Cost

We have concluded that the six-sigma-based management strategy can allow more enhanced benefits in real process improvement than do the existing techniques. The former provides especially a definite objective of the six-sigma level to ongoing process managerial measures while the latter requires quantifiable criteria to proceed with additional improvements.

5. CONCLUSIONS

The six-sigma concept is a corporate-level innovative management discipline currently prevalent in the manufacturing industry. This research explored the reasonable strategies for the improvement of construction process and productivity by combining the six-sigma with the idea of lean construction.

In-depth comparative analysis was done on the existing methods for performance improvement and the advantages of the six-sigma principle over the traditional techniques were identified. Subsequently, a basic scheme promoting the practical applications of the six-sigma concept to construction projects was suggested along with a general framework incorporated with the strategies. Then, according to the proposed procedure of the six-sigma applications, the existing process was improved in various ways through a case study of the standard unit activity groups.

The improvement levels targeted for the variations in the amount of resources and the indicators of work process performance were set in terms of the six-sigma concept. Consequently, with the help of computer simulations, the overall construction performance improved as the degree of sigma level advanced through the control of CTQ.

As a result, it is concluded that the six sigma principle has brought more benefits in generating the optimized solution sets from initial performance indices as the target processes become complicated and extended.

In order to enhance the practical effectiveness of the six-sigma-incorporated strategy, it is required that various aspects of the process should be studied using more generic construction project cases for a long period of time. The framework suggested in this study can be continuously enhanced in accordance with resulting performance by differing input variables. Furthermore, the systematic guidelines on the CTQ control of various target factors need to be developed based on the diverse characteristics of various companies because the customization of the six-sigma strategy facilitate construction firms to achieve their own process evaluation paradigm.

To achieve the aforementioned objectives, an advanced methodology for the financial feasibility analysis should be developed before the implementation of the six-sigma principle to a real project. It will provide the basis on which the improvement targets can be selectively chosen based on the practical benefits.

Consequently, an integrated management system should be established to regulate the variations of all the process constituents through the overall performance quality assessment.

Acknowledgments

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THE INTEGRATED RMC DISPATCHING SYSTEM BASED ON THE DISPATCHING CENTER APPROACH

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Abstract: Along with the development of the supply chain for the construction industry, an efficient system that coordinates cement trucks to deliver RMC (Ready Mixed Concrete) to various construction sites becomes important. This paper presents an integrated RMC dispatching model based on the dispatching center approach, which utilizes fast messy genetic algorithms (fmGA), simulation technique, and GPS to automatically and dynamically generate the optimal schedule of dispatching RMC trucks.

Keywords: RMC dispatching, fmGA, GPS, optimization, simulation

1 INTRODUCTION

Along with the development of the supply chain for the construction industry, as one of the key operations within the supply chain, an efficient RMC (Ready Mixed Concrete) delivering process becomes important to RMC batch plants. Because of time limitation of RMC delivery, the RMC plant manager usually needs to consider both timeliness and flexibility while matching up the working processes at various construction sites that call for RMC deliveries. From the business point of view, the RMC batch plant manager may want to dispatch RMC trucks to various construction sites as many as possible to maximize the profits of the plant. However, the job site manager usually wants to avoid discontinuous RMC casting by requiring a substantial number of RMC trucks waiting in queue at the construction site. As a result, when the delivering calls from various construction sites arrive in the same short period of time, it becomes troublesome for the batch plant dispatcher to quickly determine the dispatching sequence of assigning RMC trucks to construction sites. Practically the batch plant dispatcher usually dispatches RMC trucks based on his or her experiences, which usually presents the loss of the potential profits due to the inefficient dispatching schedule. Several studies [1] [2] [3] have recognized the importance of an efficient and effective RMC delivering process. However, their approaches focused on a single batch plant operation only. As many SCM (Supply Chain Management) concepts are incorporated into the operations of the RMC industry, the needs for integrating RMC batch plants are increasing. For example, CEMEX utilizes a dispatching center that coordinates its subordinate batch plants to deliver RMC to various construction sites. However, taking such an integrating approach could also increase the difficulties of developing the efficient and effective dispatching schedules for each batch plant. Therefore, a systematic RMC dispatching model based on the dispatching center approach is essential to help the dispatcher find the optimal dispatching schedules.

This research first explains the SCM concepts applied to the model development, and then incorporates the SCM concepts into building a systematic RMC dispatching model based on the dispatching center approach. This integrating dispatching model allows the dispatching center to take requests from various construction sites and coordinates its subordinate batch plants to process RMC deliveries in the dynamic environment. Several technologies, such as fmGA (Fast Messy Genetic Algorithms), simulation, and GPS (Global Positioning System) are used within the model development. In addition, a computer program called RMCDiSO II (RMC Dispatching Schedule Optimizer II) is developed to help the batch plant dispatcher easy the dispatching process. Results show that this new systematic approach along with the implemented computer program can quickly generate efficient and flexible schedules of dispatching RMC trucks to streamline the RMC dispatching operation.

2. MODEL DEVELOPMENT

2.1 *SCM concepts*

Before developing the systematic model for the RMC dispatching center, several SCM concepts related to the RMC delivering are presented. Among the SCM concepts, JIT (Just in Time), QR (Quick Response),

and BTO (Build to Order) are incorporated within the model development.

JIT: RMC needs to be delivered to the requesting construction site as the casting operation proceeds. The ideal dispatching sequence for the batch plant is that the RMC truck arrives at the construction sites as the previous one RMC truck finishes casting, which is a JIT delivering process. However, a JIT delivering process may conflict with the continuously casting if the construction sites manager requires some number of trucks waiting at the construction sites. Therefore, in this model, the total waiting duration of the RMC trucks is minimized so that the whole delivering operation is close to a JIT process.

QR: The time to delivery RMC usually has to comply with the casting operation at the construction site; therefore, such an on-call procedure requires the RMC batch plant to quick response to the customer's needs. Therefore, the RMC truck is assumed to be available for dispatching as soon as it is back to it belonging batch plant and the batch dispatches the RMC truck as soon as the RMC requests arrive.

BTO: Since RMC is produced by various formulas according to the requests from the construction sites, the RMC batch plant can manufacture the RMC only after the delivering request arrives. Such a BTO process requires the RMC batch plant to customize its product to meet the customer's demands because there are no finished products on stock. Therefore, in this model, it is prohibited for the dispatching center to redirect RMC trucks with loaded concrete to the other construction sites unless those construction sites require the same grade and amount of concrete.

Furthermore, the dispatching center that coordinates various RMC batch plants to delivery RMC to construction sites has became the call center of the RMC delivering operation. All RMC delivery requests from the construction sites are processed through the dispatching center. The dispatching center can direct RMC trucks from various batch plants to the requesting construction sites. These aforementioned SCM concepts are incorporated within the model development described in the next sections.

2.2 The dispatching center systematic model

In this study, the factors that impact the RMC delivering process are adopted from [3], in which a detailed discussion of the RMC delivering process is provided. The input factors are the number of the RMC deliveries, traveling duration between the batch plants and the construction sites, the casting duration at the construction sites, and the duration of mixing concrete. The process of determining the optimal dispatching schedule for each batch plant is performed by simultaneously applying fmGA and CYCLONE. fmGA searches through the possible dispatching schedules within the solution space by minimizing the total waiting duration of RMC trucks.

The waiting duration of RMC trucks for a dispatching schedule is determined by simulating a CYCLONE model that describes the delivering process. Two constraints−continuously casting and the capacities of the batch plants are also employed within the CYCLONE model to screen out the infeasible dispatching schedules which are generated by fmGA. In addition, GPS is applied to get the dynamic operative information of each RMC truck. The dynamic operative information of each truck is used to check whether the actual delivering process deviates from the simulated process of the optimal dispatching schedule. If the deviation of the process is over certain value, the dispatching schedule will be re optimized automatically. Figure 1 shows the scheme of the RMC dispatching system. The technologies applied in this dispatching model will be explained in the followings.

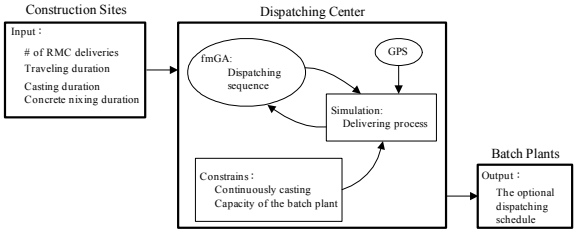

Figure 1. The scheme of the dispatching model

2.2.1 fast messy genetic algorithms

From the above development of the RMC dispatching model, it is clear that the efficiency of the RMC dispatching schedule depends on the dispatching sequence of the RMC trucks. The dispatching sequence of the RMC trucks can be treated as the permutation of the RMC deliveries from which batch plant to construction sites, which is similar to the typical traveling salesman problem (TSP) except construction sites are visited more than once. As it can be expected, the solution space could be explosively increased if the number of the batch plants, the construction sites, and required RMC deliveries increase. Therefore, the fmGA is employed to search for the optimal dispatching schedules. The total solution space of dispatching schedules can be determined by Eq. (1)

$$TS = \frac{\left(\sum_{j=1}^{m} K_j\right)!}{\prod_{j=1}^{m}\left(K_j!\right)} \times n^{TN} \quad (1)$$

Where

TS：Solution space

Kj：RMC deliveries requested by the construction site j

m：number of the construction sites

n：number of the batch plants

$$TN = \sum_{j=1}^{m} K_j$$

The fast messy genetic algorithms (fmGA) were developed by Goldberg et al. in 1993 [4]. Unlike the well-known simple genetic algorithms (sGA)" [5] [6] [7] which uses fixed-length strings to represent possible solutions, the fmGA applies messy chromosomes to form strings of various lengths. The fmGA can efficiently find the optimal solution of the large-scale permutation problem [8]. In addition, the GA-based approach has been known for its flexibility in hybridizing with other methodologies to obtain better solutions [9]. Since the departing time of each truck assigned to various construction sites is obtained by simulating the delivering process, the fmGA is adopted to integrate with the simulation methodology to find the dispatching sequence of the optimal dispatching schedule in this study. The elements and the process of the fmGA are briefly described in the following:

2.2.2 messy representation

In the fmGA, genes of a chromosome are represented by the pair (allele locus, allele value), in which allele locus indicates the position of the gene and allele value represents the value of the gene in that position. For example, two messy chromosomes ((5 0)(1 0)(3 1)(4 1)(2 1)(4 0)(5 1) and (3 1)(1 1)(5 0) may be both equivalent to the binary string 01110. As the above example shows, messy chromosomes may be "over-specified" and "underspecified" in terms of encoding bid-wise strings. Chromosome S1 is an over-specified string which has two different values in the positions of genes 1, 4, and 5. To evaluate the over-specified chromosome like S1, the string may be scanned from left to right with the first-come-first-serve rule. On the other hand, for evaluating the underspecified chromosome, such as S2, the competitive template is used. The competitive template is a problem-specified and fixed-bit string that is randomly generated or the solution found so far within the searching process.

2.2.3 messy operators

Messy operators that include the cut-splice operator and the mutation operator are used as genetic operators in the fmGA. The cut-splice operator, similar to the crossover operator in the sGA, is used to recombine different strings to create new strings. For example, as shown in Figure A cut at point 3 would result in strings ((2 0)(5 0)(3 1)) and ((6 0)(5 1)). The splice operator joins two strings with a specified splice probability Ps. For example, as shown in Figure 2, two strings ((2 0)(5 0)(3 1)(6 0)(5 1)) and ((1 1)(2 1)(4 1)) would be recombined to ((2 0)(5 0)(3 1)(4 1)) and ((1 1)(2 1)(6 0)(5 1)) after being cut and spliced.

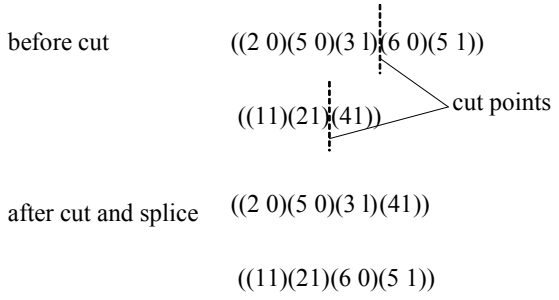

Figure 2. Cut-splice operator

The mutation operator perturbs the allele values of the messy chromosome by switching them from 1 to 0 and vice versa with a predefined probability Pm, which is similar to the mutation operator used in the sGA.

2.2.4 organization of the fmGA

There are two loops, the outer loop and the inner loop, within the fmGA. The outer loop iterates over the order *k* of the processed Building Blocks (BBs). Every cycle of the outer loop is denoted as an era. When a new era starts, the inner loop which includes the initialization phase, the primordial phase, and the juxtapositional phase is invoked. The goal of the initialization phase is to create a population of strings containing all possible BBs of the order *k*. The primordial phase filters out the "bad" genes not belonging to BBs so that the population encloses a high proportion of "good" genes belong to BBs. Two operations, the building-block filtering and the thresholding selection, are performed within the primordial phase. In the juxtapositional phase, those good genes are combined by using the selection and the messy operators to form a high quality generation which perhaps contains the optimal solution. When the inner loop of the fmGA terminates, the outer loop of the fmGA begins with processing the BBs of order k+1. In addition, the competitive template is replaced by the best solution found so far, which becomes the new competitive template for the next era. The whole process is repeated until the maximum number required k_{max} is reached. The organization of the fmGA is shown in Figure 3.

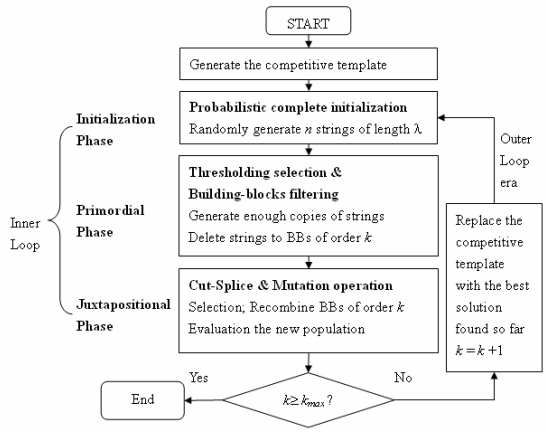

Figure 3. Organization of the fmGA

2.2.5 messy chromosome structure

The purpose of using the fmGA is to find the most efficient and effective dispatching sequence of RMC trucks from the batch plants which are subordinate to the dispatching center. Since the required number of the RMC trucks can be determined, various dispatching sequences can be treated as the permutations of assigning RMC trucks to various construction sites. Therefore, the chromosome structure is designed so that all permutations can be represented and evaluated.

First, the length of the problem is denoted as the total number of the RMC trucks that will be dispatched from the RMC batch plants at the same short of time. Since the messy chromosome representation allows strings to be "over-specified" or "underspecified", the length of the problem is used to determine the length of the competitive template only. Each messy gene within the chromosome, as shown in Figure 5, consists of three variables which identify the gene position, the ID of the batch plant, and the ID of the construction site, respectively.

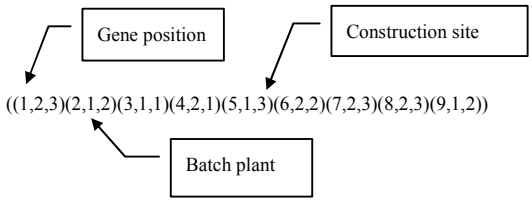

Figure 5 the messy chromosome

2.3 Simulate the delivering process

It is important that the dispatching schedule should comply with the casting processes at the construction sites. However, the number of RMC trucks that the each batch plant owns is limited; it is possible that the batch plant cannot dispatch RMC truck because no trucks have been back to the batch plant. In addition, the dispatching schedule should satisfy the constraint of continuously casting. Therefore, it is necessary to simulate the whole RMC delivering process to screen out the infeasible dispatching schedules. In the field of construction management, there are several custom-developed simulation packages specially designed for applications in construction projects. Among them, CYCLONE is one of the widely used simulation technologies because of its clear and simple symbolic structure [9]. In this research, a CYCLONE model, as shown in Figure 6, is built to simulate the delivering process. The information obtained from simulating the RMC delivering process, such as the waiting time of each truck at various construction sites and the idle time of various construction sites, are used to evaluate the efficiency of the dispatching schedules.

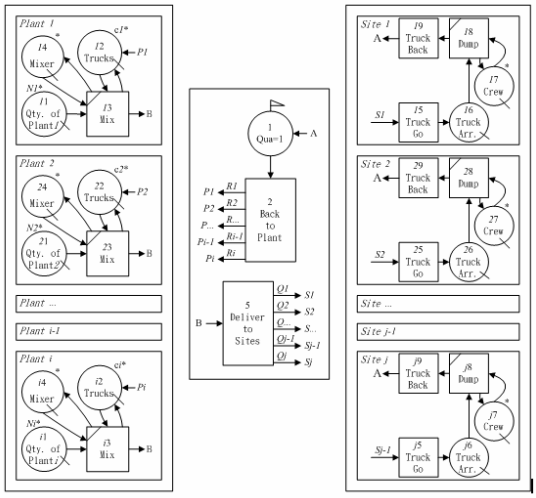

Figure 6. The CYCLONE model

2.4 The dynamic operative information

The Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. In this RMC dispatching system, the actual operative information of each RMC truck, such as casting time at the construction site, is transformed from the GPS data. The actual operative information is used to check whether the RMC delivering process is matched with the simulated optimal dispatching schedule. Once the deviation between the actual and the simulated delivering processes is over certain value, the dispatching schedule will be re-optimized automatically. In addition, since constantly retrieving GPS data is costly, a bundle service provided by the Chunghwa Telecom is employed in this study. A particular feature of this bundle service is that the GPS data can be obtained through the Internet. By taking this approach, the overall quality of GPS data retrieving can be assured. In addition, the cost of retrieving GPS data is minimized. Figure 7 shows the GPRS-based GPS provided by the Chunghwa Telecom.

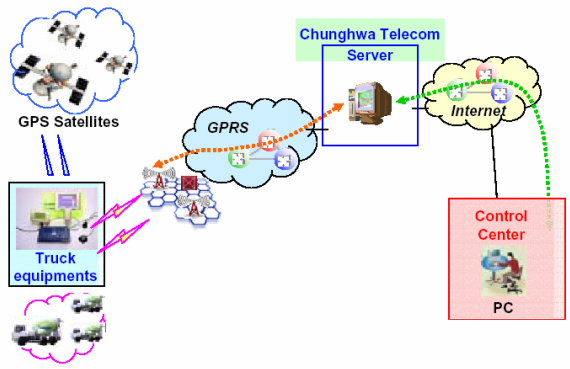

Figure 7 The GPRS-based GPS (from the Chunghwa Telecom)

3 THE RMCDISO II PROGRAM

The computer implement called RMCDiSO II (RMC Dispatching Schedule Optimizer II) is developed based on the above mentioned dispatching model. Figure 8 is the interface of RMCDiSO II. RMCDiSO II consists of three sections "Input Data", "Processing Data", and "Output Data". "Input Data" allows the users to enter the related parameters of the dispatching system, fmGA optimization, and CYCLONE simulation. "Processing Data", as shown in Figure 9, contains the optimization results and the GPS information of the RMC trucks, in which user can know how the optimization is performed. "Output Data" shows the results of the optimal dispatching schedules. As shown in Figure 10, Users can click on any of the batch plant to see the dispatching sequence of that particular batch plant. With the development of RMCDiSO II that integrates the fmGA, the CYCLONE simulation, and GPS, the process of determining a good schedule of dispatching RMC trucks to various construction has become been efficient and effective.

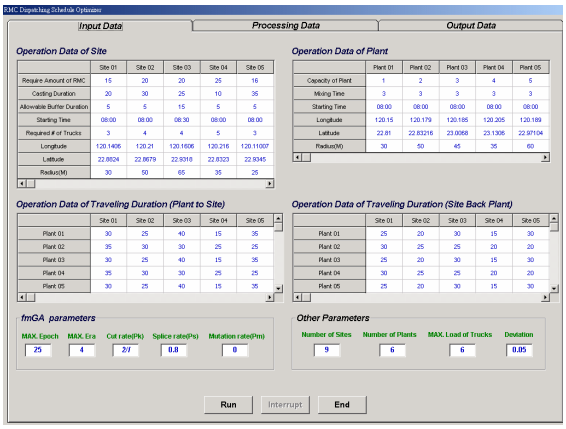

Figure 8. The interface of RMCDiSO II

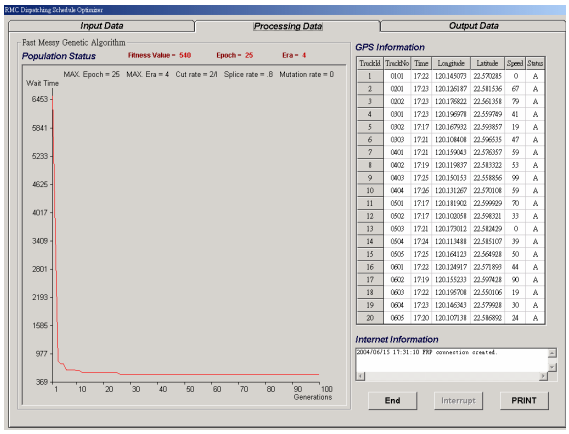

Figure 9. The data processing interface

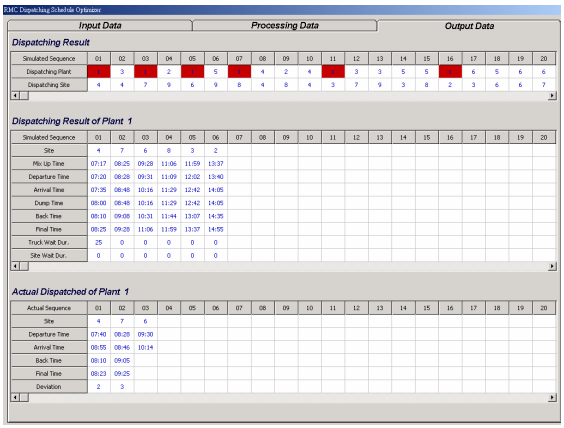

Figure 10. The result of the optimal dispatching schedule

4 CONCLUSIONS

Efficient delivery of RMC to the construction sites is one of the key operations to the RMC industry. Along with the development of the supply chain for the construction industry, a good dispatching schedule becomes more and more important. This paper presents an integrated RMC dispatching system based on the dispatching center approach. Results show that by applying the fmGA and the simulation technique to the proposed RMC dispatching model, the dispatcher at the dispatching center can quickly generate efficient and flexible schedules of dispatching RMC trucks for its subordinate RMC batch plant. In addition, the practice of the integrated dispatching system developed in this research is enhanced by employing RMCDiSO II which integrates the fmGA, the CYCLONE simulation, and GPS.

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DOOR DETECTION ALGORITHM OF MOBILE ROBOT IN HALLWAY USING PC-CAMERA

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Abstract: In this paper, an algorithm for door detection using a cheap PC-camera is developed based on the Bayesian network in a hallway where doors are located at various depth. The open/close status of the door is also important in developing a GVG-SLAM and we extracted five important door features from the image and distance data. We applied the Bayesian network algorithm and an entropy concept to increase the robustness. Experiment result shows that the proposed algorithm can help the GVG-SLAM of mobile robot by successfully identifying the status of the door.

Keywords: GVG- SLAM, door detection, low-cost sensor system, Bayesian-network

1. INTRODUCTION

The Generalized Voronoi Graph(GVG) [1, 2] is a good tool for the SLAM, especially in a hallway environment. A SLAM algorithm using the GVG (GVG-SLAM, in short) adds a node in a topologically meaningful place and localizes a robot at each node.

The weakness of the GVG-SLAM is that it cannot be used in a dynamic environment because there appears an unexpected node. In this case, the GVG-SLAM is apt to fail because it will localize the robot in a wrong place at the unexpected node.

One typical source of the unexpected node is the status and existence of the door in the hallway environment. So we need to detect door during the GVG-SLAM to mark that position as a place where an unexpected node could appear.

Previous door detection algorithms [3-7], however, cannot be used for the GVG-SLAM. The first reason is that previous results have assumed that the whole image of the door could be acquired. But a partial image of the door can be detected during the GVG-SLAM because the GVG is a set of midpoints in the hallway and thus close to the door. The second reason is that previous algorithms are designed to detect doors given the map. So those cannot be directed ported to the SLAM.

We propose a door detection algorithm which uses the partial image of the door for the GVG-SLAM. To detect the door from the image, we extracted five important door features and applied Bayesian network algorithm. To increase the robustness of a door detection result, we adopted an entropy concept [8] to represent the reliability of the result for each door.

This paper is organized as follows. In section 2, five features and the method to obtain these features are introduced. Section 3 suggests the algorithm for door detection. Experimental results of this algorithm are shown in Section 4. Finally, conclusion follows in Section 5.

2. FEATURES FOR DOOR DETECTION

The door is a part of dynamic environment whose state can be changed but the wall is a static one that is fixed. In the case of the GVG-SLAM, the status of the door can disturb localization of a mobile robot. We need to know the existence of doors and the location of them. The door has many different features such as color, material, width, height, unevenness, doorknob, etc. as shown Fig. 1(a),(b).

(a) The door

(b) The doorknob

Figure 1:Features of the door

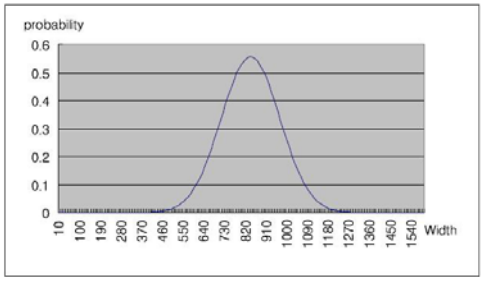


Figure 2:The Gaussian distribution for door width

Throughout this research, we have tried to make the sensor system as cheap as possible. It is important to reduce the sensor cost for commercial service mobile robots and we will not use laser range finder or experimental CCD camera for home service robot since those sensors raise the cost of the robot. A PC-camera that is connected to PC via USB(Universal Serial Bus) was selected to find vertical lines on the wall for dividing area and getting doorknob-like feature. The price of the PC-camera ranges from $30 to $150. Also we need a distance measure sensor to know depth change of the wall. For that purpose, we used inexpensive sonar sensor because our algorithm doesn't need high accuracy.
First of all, we divided the wall into a individual area by vertical lines. Each area has information about width, depth, doorknob. The width of area can be obtained from the distance of two adjacent vertical lines. The depth of area and change of open/close can be obtained from the distance measure sensor. The doorknob candidates can be obtained by the PC-camera. From these information we can aquire five features to determine the conditional possibility of the door as follows:

- The width of the area.
- The number of doorframes.
- The difference of depth.
- The existence of the doorknob.
- The state of door:[open/closed].

Now a detailed explanation of the above will be given. Firstly, the width of the area, whose value of the door in our experiment environment is assumed to be 790mm or 890mm, can be used to distinguish between the door and the wall. To represent the probability of the door, we adopt the Gaussian distribution (Fig.2) whose peak(μ) is located at 840mm and standard deviation(σ) is 127.4.
Secondly, the door has the doorframe at either or both sides. The doorframe is less than about 50mm in our experiment environment. One-side-hinged door has two doorframe areas at both sides, a two-side-hinged door has only one doorframe area at either side(Fig.3). So the area that has the narrow area at both or either side has high probability than what doesn't have any narrow at either side.
Thirdly, the door is located deeper than the wall

Figure 3: The number of doorframes

generally when the mobile robot sees them in the hallway but the depth is not fixed as shown in Fig.3.
The difference of depth is another features for door detection.
Fourthly, the door normally has a doorknob. If we find a feature looks like doorknob, we assign high probability for the area in which includes the doorknob-like features.
Finally, the door can be opened or closed. Those states can be detected by the depth of the wall. If a depth of a wall is abruptly changed compare to a previous depth record, then we assign higher probability to be the door.
In the next section, we will explain a way to calculate the probability calculation.

3. DOOR DETECTION ALGORITHM

We calculate the conditional probability of the door by the Bayesian network [9-11]. The Bayesian network is a probabilistic graphical model that represent relation between variables of conditions. Nodes represent variables and arc lines represent dependencies between variables. Bayesian networks can represent causal and probabilistic processes easily. A node which induced current node is called a parent node. And the connected node which is hanged of from the parent node is called a child node. Using Bayesian network we make the graphical model that represents the probabilistic relations between conditions (Fig. 4). Each parent node (rectangle shape nodes in Fig. 4) represents five features. One child node(ellipse shape node in Fig. 4) represents the conditional probability whether the area is door or wall. Each parent condition is independent each other. The probability whether the area is door or wall can be calculated from parents node's conditional probability as follows:

$$
\begin{aligned}
& p(X \mid DW, DF, D, DK, OC) \\
& = \frac{p(X, DW, DF, D, DK, OC)}{\sum_X p(X, DW, DF, D, DK, OC)} \\
& = \frac{p(X, DW, DF, D, DK, OC)}{p(DW, DF, D, DK, OC)} \\
& = p(X \mid DW) p(X \mid DW) p(X \mid DW) p(X \mid DW) p(X \mid DW)
\end{aligned}
\qquad (1)
$$

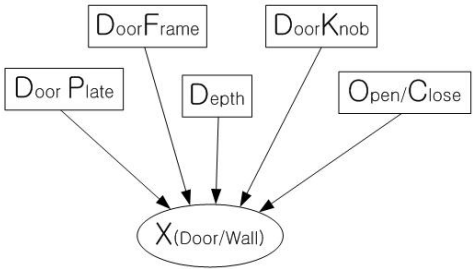


Figure 4: The Bayesian network for door detection

Table 1 : Variables

Feature	Value
DW	Width (continuous value)
DF	0,1,2
D	- , 0 , +
DK	Exist, not exist
OC	Change, not change

where DW(door width), DF(doorframe), D(depth), DK(doorknob) and OC(open/close) denote the width of the area, the number of the doorframes, the difference of depth, the existences of the doorknob and the state of door, respectively. The variable X corresponds to either a door or a wall. Each parent node has some values. Whose amounts are given as priories in Table 1.

The mobile robot starts the GVG-SLAM with the information of all in advance. Once the GVG-SLAM is started, the robot divided a acquired vision image into door/wall candidates by using vertical lines in the image. From the each candidates, five features ($DW/DF/D/DK/OC$ in Eq.(1)) are extracted and their corresponding probabilities area calculated. These possibilities area used to obtain the probability in Eq.(1).

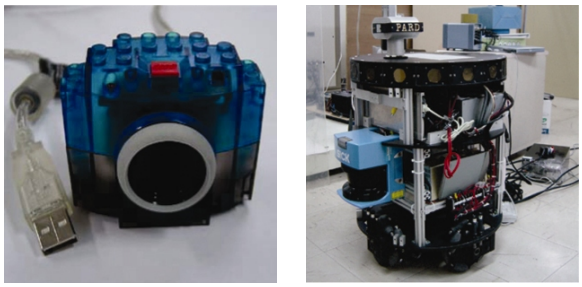
We compare the value of probability for door and for wall. If the entropy H (Eq.(2)) that measures the randomness or unpredictability is small, we determine the area is the door or the wall. But if the entropy is big, that means the result is not reliable. This area remains `the possible door area'.

$$
\begin{aligned}
H &= -p_{door}\log(p_{door}) - p_{wall}\log(p_{wall}) \\
p_{door} &= p(X_{door} \mid DW, DF, D, DK, OC) \\
p_{wall} &= p(X_{wall} \mid DW, DF, D, DK, OC)
\end{aligned}
\qquad (2)
$$

4. EXPERIMENT

4.1 Experimental devices and sensors

We applied our algorithm for the GVG-SLAM of the real mobile robot. The PARD(Postech Autonomous Robotic Device) is used(Fig. 5(a)) as a testbed. This robot has omnidirectional wheel base, LRF(Laser Range Finder), gyroscope, sonar ring that consists of 16 sonar sensors and stereo vision system. But in this experiment, we used additional PC-camera and one directional data of LRF. The PC-camera is the Logitech Quickcam(Fig. 5(b))whose price is less than $100. This camera is cheap and does not need additional device such as frame grabber. However, the image is noisy and has distortions. So accurate the image processing is not easy. Hence we only get the vertical line and door-like feature from image that is acquired from this camera. In our experiment, we also used the LRF to measure distances between the robot and the door/wall.



(a) Logitech Quickcam (b) PARD

Figure 5: Experimental device and sensor

4.2 Experimental environment and data

The experimental environment is the third door of the fifth engineering building in POSTECH(Fig. 6). We had obtained the conditional probabilities of each feature before experiments. It is difficult to get enough data of this conditional probability because the variable of `the width of the area' feature is continuous and width range is too wide. We made conditional probability for this feature as the Gaussian type probability distribution by referring 'Korea Standard door width`. The conditional probabilities of each feature are shown in Table 2∼6. We tested our algorithm using these data.

Figure 6: The Bayesian network for door detection

Table 2: The width of the area

DW	x = width of the area
$p(X_{door} \mid DW)$	$\frac{1}{1.8}\exp(-\frac{1}{2}(\frac{x-840}{127.4})^2)$
$p(X_{wall} \mid DW)$	$1 - p(X_{door} \mid DW)$

Table 3: The number of doorframe

DF:	2	1	0
$p(X_{door} \mid DF)$	0.6	0.5	0.4
$p(X_{wall} \mid DF)$	0.4	0.5	0.6

Table 4: The difference of depth

D:	+	0	-
$p(X_{door} \mid D)$	0.5	0.04	0.91
$p(X_{wall} \mid D)$	0.5	0.96	0.09

Table 5: The difference of depth

DK:	Exist	Not exist
$p(X_{door} \mid DK)$	0.6	0.03
$p(X_{wall} \mid DK)$	0.4	0.97

Table 6: The state of door:[open/closed]

OC:	change	No change
$p(X_{door} \mid OC)$	0.94	0.5
$p(X_{wall} \mid OC)$	0.06	0.5

4.3 Experimental result

In the hallway, there are four types of doors. Most ordinary door type is shown in Fig. 7(a). The door in Fig. 7(b) has some different features – no depth difference, only one doorframe. The door in Fig. 7(c),(d) has only one doorframe at one side and assist door. The assist door is narrower than common door. At first we close all doors and ran the robot to detect them. The result of first experiment is shown in Fig. 8. We omitted the data of the wall area because the conditional probability of those areas and entropy value are very small. So we can conffidently determine that these areas are the wall.

Secondly we opened some of the doors and did the same experiments. The result is shown in (Fig. 9). After an opening of 6th area, conditional probabilities of that area and the second area that has the same features with 6th are raised and the entropies are decreased. The algorithm determines those areas as the door area. We obtained the same result for the 15th and the 19th areas. In the cases of 11th and 12th areas, the conditional probability is increased but the entropy is increased after their opening. We call those area as `a possible door area'. The 16th and 18th areas are rarely used. We have set these area closed. But we can decide that those areas are `the possible door area' because those closed state

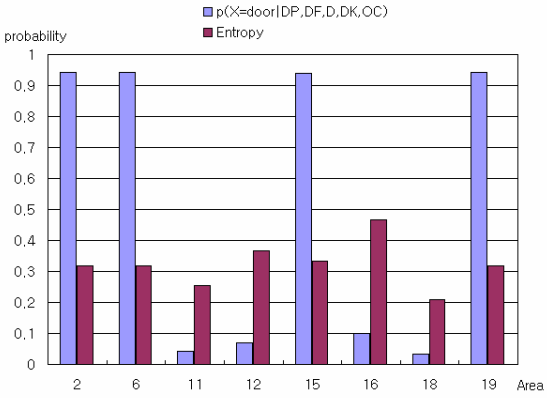


Figure 8: Experimental result before door open

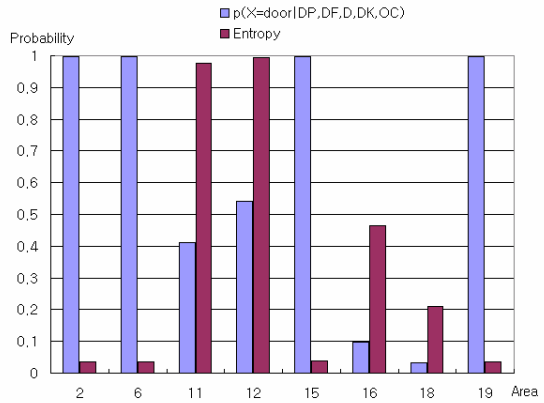


Figure 9: Experimental result after door open

area have many features similar to the real door. The mobile robot knows that this area could be opened in the future.

5. CONCLUSION

In this paper, we proposed a method to detect the door for the mobile robot during a GVG-SLAM by using a cheap PC-camera. The mobile robot acquires information of the wall with sensors. Then the robot selects five features that can match each area into either the wall or door. Bayesian Network is used to obtain the conditional probability whether the area is the door or the wall. The robot has the conditional probability of each feature before it makes a GVG-map. The probability value and the entropy determine whether the area is the door or the wall. Experiments show that this method can help the mobile robot make more complete GVG-map. Hence, the robot can estimate it's location more robustly.

Our method can be applied to a non-high performance system because this method uses probabilistic concept.

Since we have not conducted many experiments yet, we couldn't show robustness of our algorithm in other environment. We will verify how this algorithm

can be used to aid the GVG-SLAM of mobile robot quantitatively. Lastly, we need more data of various environments to make the area 11,12,17 and 18 can be decided as a door.

Acknowledgments

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A Study On Path Guidance System Of Guide Robot For Visually Impaired

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Abstract : In this paper, earth coordinate of the guidance robot for the visually impaired is detected by using GPS (Global Position System), and the system which leads the visually impaired to position information (TM coordinate) in Korea is achieved through map-matching with electronic map. The visually impaired need more information about the walking path than ordinary people when walking outdoor. Therefore, we studied implementation which can guide the visually impaired more safely through map-matching with GPS signal by making electronic map for the visually impaired.

Keywords: Guide Robot, GPS, Map-matching, GIS,

1. INTRODUCTION

According to the research on the handicapped person in 2000, the number of the visually impaired in Korea is assumed by 180,000 persons where is more than double in number than 70,000 persons of 1995. While, welfare facilities for the visually impaired are still in a primitive level as at most Braille type block on side-walk or signal lamp's walk guide by sound.

The outside activities of the visually impaired are heavily depending upon the use of white canes or guide dogs. However white cane is not an ensuring mean of safety and guide dog is not cost effective, not in wide use. Assistant equipment for the visually impaired has been on demand to address the problems and guides them safety.

Recently, RTA(Robotic Travel Aids) system using mobile robot is widely studied as a guide system for the visually impaired. HARUNOBU of the Yamanashi University in Japan is the representative example.

In this paper, the implementation that the guidance robot for the visually impaired guides the visually impaired in safety is studied in this paper.

Because the guidance robot for the visually impaired should guide to the destination in safety, the path of the guidance robot could be different from that of the ordinary people. Therefore, the electronic maps concerned about the characteristic of the visually impaired are necessary.

In this paper, the walking path and destination are determined by making the electronic map for the visually impaired including directions, distance, and types of the walking path which are necessary when the visually impaired are walking outdoor. Also, the system that the location of the guidance robot is presumed by using GPS signal and then the guidance robot guides the visually impaired in safety through map-matching between the electronic map and GPS signals is implemented.

The system based on the PDA especially enabled the visually impaired to walk alone carrying with the PDA and the GPS receiver without the guidance robot.

2. SYSTEM IMPLEMENTATION

Figure 1 shows the system conception of the visually impaired walk with the guidance robot wearing bone-conduction headphone and carrying with PDA. The bone-conduction headphone is the thing that provides necessary information to the visually impaired as sound, and PDA matches GPS signal from the robot by radio communication to the map. In order to input the destination where the visually impaired want to go, the braille keypad is

attached on the screen of PDA.

Figure 2 shows the block diagram of the guidance system. In generally, the digital map is focus to car navigation system and difficult to apply to blind man guidance. Therefor, we composed the guidance system with two part, guardian system and user system. First system is made a new map layer for blind man, next is guidance system using the map layer.

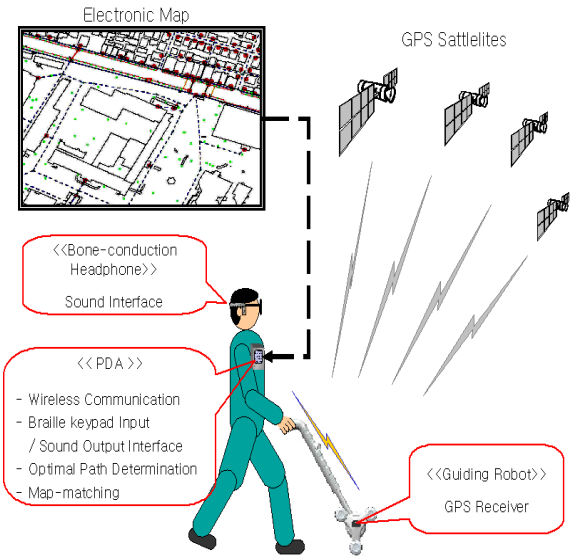


Figure 1. System Conception

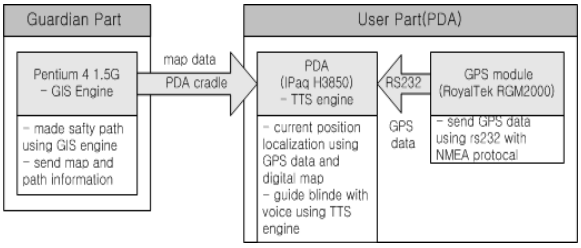


Figure 2. Syste block diagram

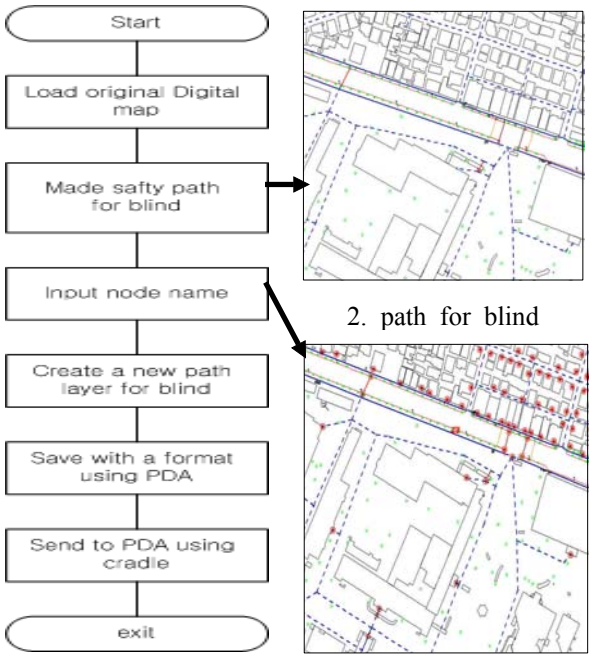
2.1 Guardian Part program base on PC

The electronic map for the visually impaired includes the information which is necessary while walking. The 1:1000 electronic map has layers which consist of information for the visually impaired. Compared to the general electronic map, the link that has the directions, distance, and types of the walking path for the visually impaired and the node that points out the destination which the visually impaired can select are added.

The visually impaired are difficult to walk in the sidewalk without the braille block, the road, the crosswalk, and the overpass etc. Therefore, the proper way to detour according to kind of path for safety must be selected in case of deciding the optimal path.

The type of path in the link are the sidewalk with the braille block and without the braille block, the road that cars and people pass together, the crosswalk, the stairs, and the overpass. The safer path is selected among each same distant paths using different weights as dangerous levels.

Figure 3 shows the electronic map for the visually impaired around Inha University. Solid lines and dotted lines that are shown in figure 2 are paths, the "link", that the visually impaired can walk, and ◎ indications are the "node" that indicates the destination that the visually impaired can select. The family of the visually impaired can update the electronic map as the visually impaired want because the links and the nodes in the electronic map could be modified in the softwares based on PC.



1. Flow chart

2. path for blind

3. the layer for blind

Figure 3. Guardian program

2.2 User Part program based on PDA

Figure 4 show the diagram of the user program in PDA.

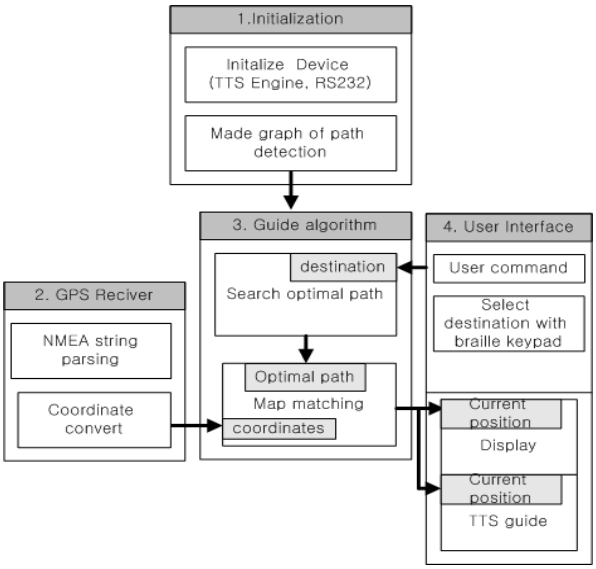


Figure 4. The diagram of PDA system

Initialization is include device initialize and create a undirected weighted graph for searching the path. we presented the graph with adjacency-list method. Each vertex in the graph have maximum four edge and define six weight values for distinct path kind.

GPS receiver part processing NMEA string parsing and coordinate convert from WGS84 to TM in korea using Molodensky-Badekas model.
In the NMEA0813 sentences, we used GPRMC sentence for position information, use PDOP, and SNR from GPGSV sentence for estimate the error of GPS.

The user interface is composed braille keypad input system and voice output system using tts engine. hence, user can select the destination name with ARS method. In addition we made braille keypad using PDA touch screen.

The guide algorithm have path detection algorithm and map matching algorithm. While the optimal path for the ordinary people is the shortest path, that for the visually impaired should be concerned about safety first of all. In this paper, the method which decides the optimal path for safety of the visually impaired is proposed using Back Tracking algorithm. Also, the graph for the determination of path combines the necessary information for the visually impaired's walking. Back Tracking algorithm is DFS (Depth-First Search). DFS is that any search algorithm which considers outgoing edges of a vertex before any neighbors of the vertex, that is, outgoing edges of the vertex's predecessor in the search. Extremes are searched first. This is easily implemented with recursion. An algorithm which marks all vertexes in a directed graph in the order they are discovered and finished, partitioning the graph into a forest. If the value exceeds the determined limit in the Back Tracking algorithm, then it comes back to the vertex which was selected in the previous step. In the process of searching the optimal path using Back Tracking algorithm, the path detours in case of danger. Furthermore, if the visually impaired want to minimize the number of overpasses and crosswalks, not the shortest path but the optimal path could be selected through the adjustment of the number of specified type.

The modified point-to-curve matching method is used for map-matching method. The point-to-curve matching method is the method that projects to the nearest arc after measuring the distance from each received points. Because this method has the advantage of easy and fast operation due to little amount of measuring, it is more efficient than other algorithms in the map-matching method. However, this method could mismatches to the wrong road around two roads near the crosswalk due to the error of GPS. In this paper, the way of a 1st order equation that minimizes error in the data including error is used by the information of robot's moving direction. In addition, the method that the error is revised at the next received point is added to improve map-matching using error between received and matched point.

3. EXPERIMENT RESULT

For this experiment, RGM2000 GPS reception module of Royaltec company is attached on IPAQ H3850 PDA using RS232C. The produced information of electronic map is stored in PDA through PDA cradle. PDA receives GPS information by NMEA way through RS232c, and map-matches to the received map information, then composes guidance information through drawing the location in Korea, and guides as sound through TTS(Text-To-Speech) engine.

Figure 5 shows GPS receiver and PDA that composes for an experiment.

Figure 5. The experiment system
(left is input screen, right is guide screen)

In order to recognize how much GPS reception signal and actuality walk path show difference, the GPS signals were received around actual residental walking paths. GPS data that received through PDA simulated in PC.

Figure 6 indicates is targeted real path for experiment. And GPS signals that were received by actual walking around residental area in the Inha university. Figure 7 show the received GPS data. Figure 8 shows the map matching result.

The result shows that except for area A, B, C, other path's data show good results almost same as actual walking.

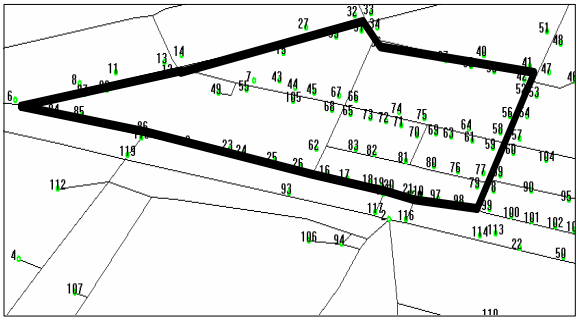


Figure 6. Real Path

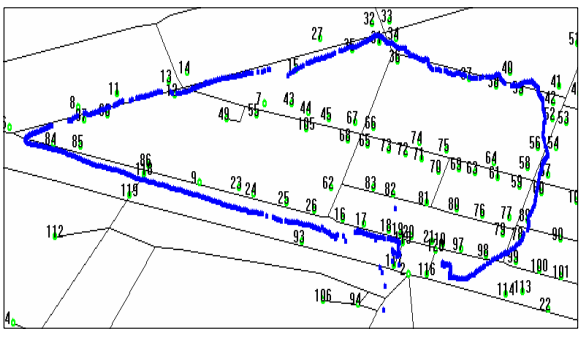


Figure 7. GPS Data

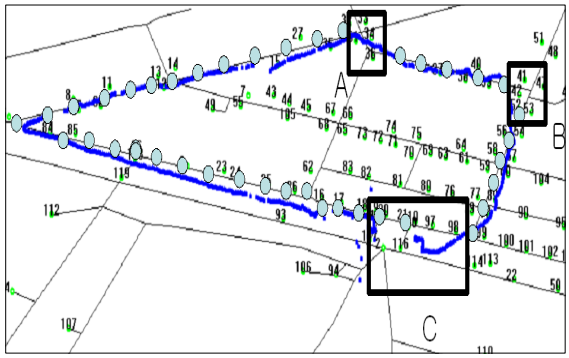


Figure 8. Map matching result

The area of A, B is a alley, and area C has a high-rise building. Therefor, there are serious multi-path error. The table 1 shows the mismatching error(Nmber of mismatching data / total Number of received data) in two different environment. The table describe the environment with PDOP value. With PDOP lower than 6, can get good matching result. In the case of cycle slip and PDOP>10, the GPS data is have too much error to use it. Therefor, the high PDOP value means the bad environment for receiving GPS signal.

Table 1. Influence of the environment

	Experiment 1	Experiment 2
Num of data	770	800
Cycle slip error	5%	20%
PDOP>10	6%	19%
10>PDOP>6	11%	25%
PDOP<6	73%	46%
Matching error	15%	35%

Even if, with lower PDOP GPS data, also have big absolute error. Figure 9 shows the error and PDOP in a rectilinear movement.

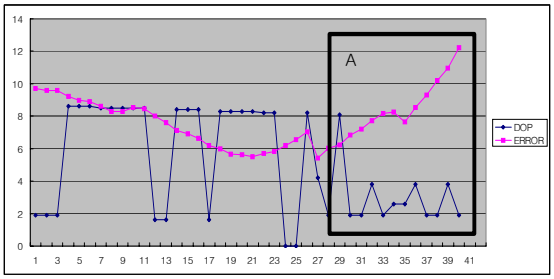


Figure 9. Error and PDOP in Rectilinear movement

In the area A GPS data have lower PDOP value, but

the error is more than 10m and become higher. Therefor the rate of PDOP is also a important factor to estimate GPS error.

4. CONCLUSION

In connection with the implementation of guidance robot for the visually impaired, map-matching between GPS and electronic map which is for self localization and determination of right path of robot is studied in this paper.

map-matching received GPS signal to the optimal path in the electronic map, although it is similar with real walking path, a few miss map-matching cases occurred at the difficult points to receive.

In case of big error, that is, map-matching is failed, if map-matching is achieved not only depending on the GPS signal but also with INS of robot, the result may be more correct. Furthermore, although the starting point of the guidance robot cannot be known exactly using GPS reception signal, it is helpful to implement if the starting point is detected through the vision sensor and so on.

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POSE OF I-BEAMS FOR CONSTRUCTION SITE AUTOMATION

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Abstract: Automation of construction processes can result in reduced project costs and increased worker safety. A process that lends itself to automation is the picking and placing of objects. However, determining the pose (position and orientation) of an object is critical. LADAR (laser detection and ranging) data provides 3D information of a scene, but the data are noisy, contain outliers, and have phantom points along edges of objects. A preliminary algorithm to preprocess the data and to compute the object pose is presented. The algorithm was validated through comparison with experimental measurements.

Keywords: Binning, LADAR, object recognition, object segmentation, pose determination.

1. INTRODUCTION

Inefficiencies in component, material, and trades tracking on construction sites has been repeatedly voiced at the National Institute of Standards and Technology (NIST) workshops (Automated Steel Construction, Data Exchange Standards at the Construction Site) as a top concern. Improved asset tracking systems will enable both leaner construction and enhanced security, as well as lay the foundation for levels of automation envisioned in an Intelligent and Automated Construction Job Site. The combination of LADAR scanning technology, real-time object recognition, automatic identification, and tracking technologies provide powerful potential mechanisms for assessing real-time status of construction site operations and lay ground work for autonomous construction systems.

The Construction Metrology and Automation Group (CMAG) of NIST has an ongoing effort in Construction Object Recognition and Tracking [1]. Current efforts in this project are focused on determining the pose of an object given a point cloud (in the form of x, y, z data) of a scene as obtained from a LADAR. The objective of these efforts is to rapidly determine the pose of an object, without user intervention, so that an automated crane can locate the object, move towards it, and align itself (i.e., gripping mechanism) to pick-up the object. A more exact position and orientation of the object will be determined as the crane nears the object using on-board sensors.

The current efforts include developing an algorithm to segment the data (remove data not belonging to the object of interest) and to determine the pose of a targeted object, an I-beam in this case. The I-beam specifications are inputs to the algorithm and are used to create a bounding box that encloses the I-beam. This bounding box is used as a means to eliminate extraneous objects from the scene by comparing the bounding boxes of identified objects with that formed from the I-beam specifications.

This paper presents a summary of the initial work involved in implementing an algorithm to post-process data obtained from a data base of I-beam specifications as well as data obtained from experiments conducted to quantify the uncertainty of the algorithm. The overall algorithm is composed of several separate sub-algorithms. These will be discussed in the next sections.

2. DATA SETS

Two data sets are involved with the processing. The first is a set containing known objects and is the I-beam data base, which is a file that consists of groups of I-beam specifications, such as the beam name or identifier, its length, its depth, flange width, and web and flange thicknesses. After reading the data base, the main program converts the information to 24 points that represent each I-beam (Fig. 1).

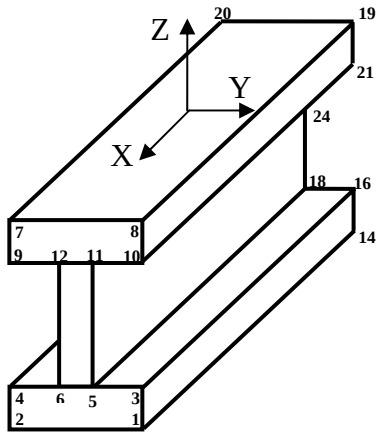


Fig.1. I-Beam vertex representation.

The second data set is one of the scanned LADAR data sets that are given as files of x, y, z points, one triplet per line, relative to the scanner axis system. The number of points in these data sets ranges from about 10 000 to about 80 000 (highest scanner resolution).

3. BINNING ALGORITHM

In order to make the scanned data sets more manageable, the data points are accumulated into volume cubes or *voxels* that encompass the entire range of the data set. This process is called *binning*. The algorithm prompts the user for the number of *x*, *y*, and *z* axes partitions which are used to determine voxel size. The size of each voxel is calculated as a triplet (*dx*, *dy*, *dz)*, e.g., $dx = (xmax - xmin)/(\#$ of partitions in $x)$. Each (x, y, z) point is associated with an (i, j, k) value for each bin. In terms of *x*, for example, this is computed for each point r of the scanned data as $i(r) = \text{fix}[(x(r) - xmin)/dx] + 1$, with due consideration of the boundary voxels. Similar index calculations are performed for $j(r)$ and $k(r)$ for each of say *N* points. Once the $(i(r), j(r), k(r))$ indices are computed for each point, the bin count (number of points) per voxel can be determined. The bin count of all voxels is initially set to zero. Due to the binning, many (x, y, z) points will have the same $(i(r), j(r), k(r))$ indices. The algorithm iterates by starting with index triplet $(i(1), j(1), k(1))$ and finding all matches of this triplet by a simple linear search. The number of matches, say *M*, gives the bin count for the $(i(1), j(1), k(1))$ voxel. These matched indices are then eliminated from the $(i(r), j(r), k(r))$ list and a new allocated list is formed of length *N-M*. The old list is deallocated. This begins to reduce the number of $(i(r), j(r), k(r))$ triplets that need to be linearly searched. The algorithm then begins again with the new $(i(1), j(1), k(1))$ triplet, finds the matches, counts them for that voxel and then eliminates those triplets. The process continues until there are no more $(i(r), j(r), k(r))$ triplets. All voxels would then have a bin count associated with them. Many would have a bin count of zero.

The binning process was selected instead of surface fitting for several reasons. It allows objects to be modeled by polygon structures, since it is not necessary to develop a detailed model of an object in order to align an automated crane with the object. Polygon models provide sufficient structure for alignment and they allow fast comparisons with similar polygon models of the ideal structures by only needing to match relatively few vertices.

4. VERTICAL VOXEL STRINGS

LADAR scans can generate a large number of mixed or phantom pixels in a scan [2] (see Fig. 6). These phantom pixels are usually caused by a portion of the beam being reflected from an edge of an object and the other portion being reflected from another object behind the first. The resulting measurement places a point somewhere between the two objects. This section describes a process used to eliminate these points as well as eliminate such points as ground hits.

The algorithm is based on the idea that those columns with floor hits or phantom pixels would have a number of voxels with small bin counts and in general very few voxels connected to them in the column. It should be noted that voxels can have more than one phantom pixel in them depending on voxel resolution. By a connected voxel, we mean one with a nonzero bin count either directly above or directly below. These are also referred to as *neighboring voxels*. A vertical string of voxels is defined to be the set of non-zero voxels in one column that are direct neighbors of each other. The most significant vertical voxel string in a column is the longest string in each column. This is determined by examining each vertical column of voxels and associating a value of one in a buffer for that column if a bin is non-zero, otherwise the buffer is set to zero. The string length and maximum string length for the column are initialized to zero. Each voxel up the column is examined. If the buffer value is one then the string length is incremented and the maximum string length is set to the current string length if it is longer than a previous string length in the column. Once the buffer becomes zero the current string length is reset to zero and the next voxel is examined until the column is finished. The maximum string length per column is automatically produced. Also, the maximum overall string length is the maximum of all of the column string lengths. Columns that include those voxels that are to be eliminated are determined by comparing the maximum string length up a column with the maximum overall string length. If the maximum column string length is less than a prescribed fraction of the maximum overall string length then the bin counts in that column are all set to zero. Currently that factor is selected interactively, but future algorithm enhancements will include a more general factor determination. Columns with floor hits or phantom pixels usually have maximum column string lengths of one or two as opposed to maximum column string lengths of 40 or 50 or more for tall objects, again depending on voxel resolution.

5. SEGMENTING OBJECTS

Once the outlier voxels, such as phantom pixels and ground hits have been eliminated, entities called *objects* can be identified. The basic premise of the object segmentation portion of the overall algorithm is that objects are made of neighboring voxels. Thus this portion of the algorithm accumulates neighboring voxels into object structures. The sub-

algorithm used here is based on one proposed in Nikolaidis and Pitas [5] for calculating the volume of connected components in 3-D. The process starts by constructing a three dimensional array, called the *mask array*, of the same size as the voxel array and assigning the value one to the mask element (i, j, k) associated with the voxel indexed (i, j, k) if that voxel element is non-zero, otherwise the mask array element is set to zero. The segmentation proceeds by first finding a non-zero mask element and setting it to zero after storing its voxel information on a stack. It then proceeds with setting to zero each of the mask array elements for every neighboring non-zero mask element that is found, and then placing the associated voxel information associated with each of those mask elements on a temporary holding stack. For those neighbors, their neighbors are examined in an outward expanding group of neighboring voxels. When there are no more non-zero neighboring mask elements to be set to zero, the stack is unloaded into an object structure. Setting the mask array elements to zero for all of the voxels in an object means that when the algorithm goes back to the mask array to start another object it won't find a mask element associated with the object just created.

6. PRINCIPAL AXES

In order to determine the pose of a defined object, it is useful to identify a set of axes that represent the distribution of the voxel centers about the center of data mass. If an object is defined by a group of voxels, each with a center (x, y, z) associated with it, then a set of orthogonal axes relative to the center of data mass can be determined that extend in the directions of the longest axis of data, the second longest, and the third longest. These are called the *principal axes*. For a further discussion of this algorithm and its other applications in graphics see Lengyel [3]. Objects that are only linear or planar do not have a full set of principal axes and will not be considered as legitimate objects in this study. The principal axes are representative of the directions in which the data varies. To determine the principal axes assume that points $P_1, P_2, \ldots, P_N$ represent N points in 3D Euclidean space. We first calculate the mean position or center of data mass m by

$$m = \frac{1}{N}\sum_{i=1}^{N} P_i \qquad (1)$$

We then construct a 3 x 3 matrix called the covariance matrix

$$C = \frac{1}{N}\sum_{i=1}^{N}\left(P_i - m\right)\left(P_i - m\right)^T \qquad (2)$$

This covariance matrix is a symmetric matrix that represents the correlation between each pair of $P_i = (x_i, y_i, z_i)$ points. The natural axes of the set of points are determined as follows. First, the eigenvalues of C are found and ordered largest to smallest. The associated eigenvectors are then found. The eigenvector associated with the largest eigenvalue points in the direction of the points having the largest variation, generally the longest axis. The eigenvector associated with the next largest eigenvalue points in the direction of the next longest axis and similarly with the third. The process of developing the principal axes is related to the statistical technique called principal components analysis. For a discussion of this topic see Montgomery, et al. [4].

7. CREATING BOUNDING BOXES

Although there are uncertainties in locating the boundaries of LADAR scanned objects, it is possible to establish reference surfaces and vertices that can be used to compare against associated reference surfaces and vertices on the I-beams given in the data base. Due to the statistical uncertainties of locating object edges, we use polygons to bound the object. One advantage of this approach is that if a polygon is also constructed around the ideal object from the database, such as an ideal I-beam, then comparisons can be made between well defined polygons. In the case of I-beams, polygons defined as *bounding boxes* are used. The approach is relatively straightforward. Every legitimate object is defined in terms of voxels and each of the voxels has a center (x, y, z) point. Once an object, in particular the I-beam, has been identified in terms of voxels then the vector from the LADAR scanner origin to each voxel center in the I-beam is projected against the principal axes. The lengths of the different sides of a box enclosing all of the voxels defining the I-beam is given by the difference between the maximum and minimum values of the projections along each of the principal axes. The vertices of this box are then easily determined. Next the specifications for an I-beam in the database can be used to construct the 24 points defining the I-beam (Fig. 1). These points can also be used to generate the principal axes for the reference I-beam. Once these principal axes are known and the distance to the center of data mass of the measured I-beam from the scanner is known, it is then possible to construct the x-, y-, and z-rotations to transform the reference I-beam model and map it over the bounding box of the measured I-beam data (Fig. 4). Then a sum of squared errors function can be used to compute the error between the associated vertices of the reference I-beam model and the measured I-beam bounding box. The segmented object will be associated with the known object which yields the smallest error.

8. EXPERIMENTS

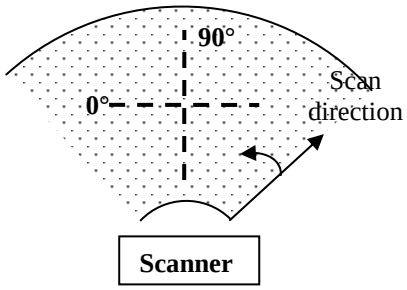
A series of scans were conducted to determine the uncertainty of the pose calculations, the influence of point density on pose uncertainty, the influence of point of view of the scanner relative to the object on pose uncertainty, and the ability of the algorithm to differentiate between two objects of similar shape. In these experiments, an I-beam in an uncluttered environment was scanned using a LADAR with a manufacturer specified range uncertainty of ± 2.5 cm (best case) and ± 5 cm (worst case). The experimental parameters include type of I-beam (2 I-beams), angle of the I-beam in its coordinate frame (0°, 30°, 45°, 60°, and 90°, see Fig. 2a), and point density (3 levels).

For each I-beam rotation, three scanner angular increments (horizontal and vertical) between points were used: 0.072°, 0.108°, and 0.18°. The lowest increment corresponds to the highest point density. Three scans were obtained at each angular increment for a total of 9 scans for each I-beam rotation angle. A total of 90 scans were obtained.

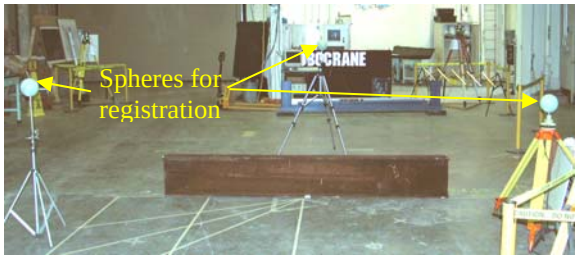
To measure the rotation of the I-beam, the four corners of the top flange were measured with a laser-based site measurement system (SMS) that has a manufacturer stated accuracy of less than 2 mm. These measurements were taken every time the beam was moved. Additionally, there were three spheres (see Fig. 2b) located within the scene for registration purposes and several points on each sphere were measured. This allows for the determination of the transformation matrix between the two coordinate frames (LADAR and SMS). Points on the scanner were also measured using the SMS to locate the scanner in the SMS coordinate frame.

9. POINT REGISTRATION

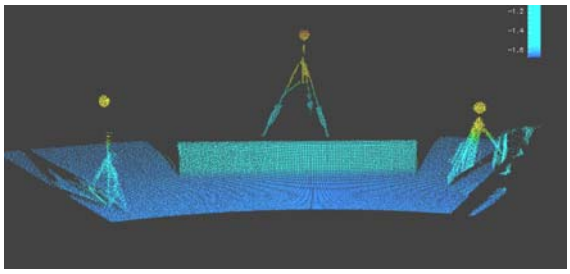
In order to estimate uncertainties of the pose of the I-beams, a transformation between the axis system of a site measurement system (SMS) and the LADAR coordinate frame had to be determined. This was done by assuming that points in both axes systems fell into a global axis system and a rigid body transformation was developed using an iterative algorithm that determined the transformations that linked the SMS and LADAR coordinates. A full discussion of the details of this algorithm is beyond the scope of this proceedings article and will be published elsewhere.



a. I-beam orientation.



b. I-Beam at 0°. Spheres used for registration.



c. Point cloud of scan.

Fig. 2. Experimental set-up.

10. PRELIMINARY RESULTS

At the time of the publication of this paper, only one data set was examined. When all the data have been examined, a discussion of the uncertainties of pose determination will be published.

Figure 3 shows a stacked contour plot of the objects identified in a scan. In the first stage of the segmentation algorithm applied to this data set, 14 objects were identified, using a voxel size of dx = 0.123 m, dy = 0.107 m, and dz = 0.027 m. In the second stage of the segmentation algorithm, all objects that did not have 3 principal axes were eliminated and the remaining object was the I-beam. Figure 4 shows the point cloud and the bounding boxes around the ideal I-beam (green box) and around the LADAR measured data as represented by the centers of the voxels comprising the measured I-beam (blue box). The measured box is slightly wider and shorter than the ideal box. This could be a result of the selected voxel size and will be investigated further.

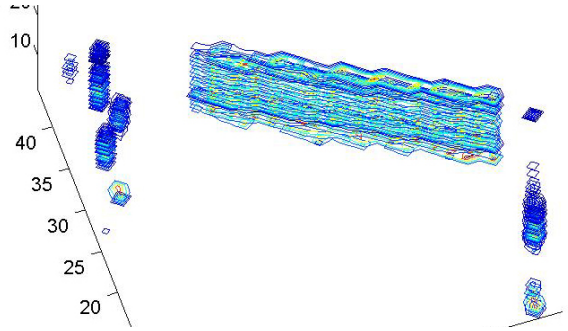


Fig. 3. Segmented Objects.
Angle = 0°, medium point density.

To estimate errors and uncertainties of these bounding boxes, measurements of the four corners of the I-beam, as it rested on the floor as shown in Fig. 2b, were compared with those obtained analytically. The four points selected are the corners of the top flange that correspond to points 8, 7, 19, and 20 in Fig. 1. Table 1 gives the measurement results of these points in the SMS coordinate system.

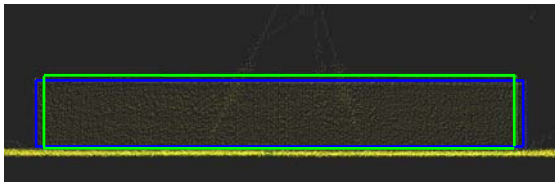


Fig. 4. Bounding boxes. The narrower, taller (green) box shows ideal I-beam. The wider, shorter (blue) box encloses the segmented I-beam.

Table 1
Top Flange Points in SMS Coordinates (m)

Point	x	y	z
8	8.5644	-3.7518	-1.3459
7	8.3901	-3.7738	-1.3492
19	8.2310	-0.7201	-1.3569
20	8.0545	-0.7403	-1.3581

The points in Table 1 were used as the "truth" or reference measurements because the maximum standard deviation of all the measurements was 3 x 10^{-4} m. Table 2 gives the same points as computed from the bounding box for the scanned I-beam.

Table 2
Top Bounding Box Points in Scanner Frame (m)

Point	x	y	z
8	-4.7790	4.9337	-1.1618
7	-4.8648	5.0691	-1.1628
19	-2.2990	6.5057	-1.1654
20	-2.3849	6.6411	-1.1665

In order to determine the transformation the SMS coordinates to the scanner reference frame, the points on the three spheres shown in Figs. 2b and 2c were measured using the SMS system and the LADAR. Best fit sphere models were then fitted to the measured data and the estimates of the centers in the SMS frame and the scanner frame were made.

An additional point that was used to determine the transformation matrix was the center of the scanner. The center of the scanner cannot be physically measured. Therefore, several points on the scanner were measured with the SMS system and the scanner center, in the SMS coordinate frame, was derived based on these measurements. The coordinates of the scanner center in the scanner frame is (0, 0, 0) by definition.

These four points represent the four points common in the two coordinate frames. Using the approach described in Section 9 to transform the coordinates in the SMS to the scanner frame, a rotation matrix is determined. This rotation matrix indicates that the main rotation is about the Z-axis with rotations about the X- and Y-axes approximately equal to 0.

Transforming the four points in Table 1 we obtain:

Table 3
Top Flange Points in SMS Frame Transformed to Scanner Frame (m)

Point	x	y	z
8	-4.8635	4.9218	-1.1966
7	-4.9594	5.0691	-1.1995
19	-2.2815	6.5452	-1.2165
20	-2.3767	6.6952	-1.2173

The deviations between the coordinates in Table 3 and those in Table 2 are given in Table 4.

Table 4
Deviations = [Table 3 – Table 2] (m)

	X Error	Y Error	Z Error
8	-0.0845	-0.0119	-0.0348
7	-0.0946	0.0000	-0.0367
19	0.0175	0.0395	-0.0511
20	0.0082	0.0541	-0.0508
Mean	-0.03835	0.02043	-0.04335
Std. Dev.	0.05938	0.03141	0.00881

The location of the I-beam in the scanner frame can be found from Table 2. The center point of the top of the bounding box is computed from the four corner points as (-3.5820, 5.7874, -1.1641) m. A similar calculation from the transformed SMS points in Table 3 shows the center point to be (-3.6203, 5.8078, -1.2075) m. The difference between the transformed coordinates and the scanner coordinates is (-0.0383, 0.0204, -0.0434) m. These deviations and those in Table 4 are within the accuracy of the LADAR used. It should also be noted that the center point in the scanner frame has an expected offset

from "true" center. This offset is due to the fact that there are many more measurements of the I-beam on the side of the I-beam that is closer to the scanner; thereby biasing the center towards this side (Fig. 5).

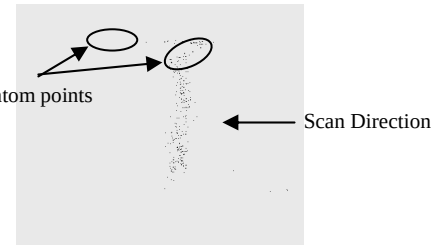


Fig. 6. Point cloud of I-beam viewed along the longitudinal axis of I-beam. Note the phantom points at both edges of the top flange.

As mentioned earlier, the rotation matrix (SMS to LADAR frame) shows that the main rotation is about the Z-axis. Therefore, only the Z-rotation will be discussed in the following paragraphs.

One of the experimental parameters was the angle of the I-beam relative to the scan direction (see Section 8 and Fig. 2a). For the data set that was examined, this angle was 0° (Fig. 6) in the I-beam frame. From Table 2, it can be shown that the longitudinal vector of the I-beam forms an angle 32.2° counterclockwise from the -X axis of the scanner frame.

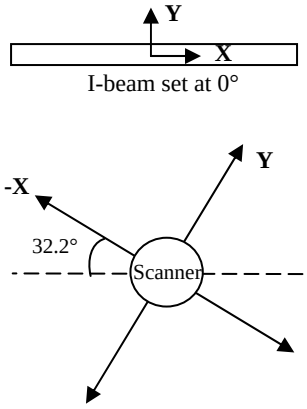


Fig. 6. Rotation of I-beam relative to the scanner coordinate frame.

The rotation about the Z-axis of the I-beam as determined using the algorithm is 32.2° in the scanner coordinate frame. This compares exactly with the measured pose of 32.2°.

11. SUMMARY AND OBSERVATIONS

Preliminary findings of an experiment to determine an object's pose are presented. The algorithms to segment an object and to analytically determine the object's pose are described.

Although the LADAR scan of the I-beam and its surroundings from one perspective generated noisy data, the techniques of vertical voxel string identification, object segmentation, bounding box construction, and rigid body rotations seem to be a set of viable tools for identifying objects, as long as there is prior knowledge of what the likely object candidate is. Identification of objects in this context means obtaining sufficient information about the object and its pose to enable differentiating it from other objects and aligning an automated crane to pick up the object.

Based on the measurements from one experiment, the algorithm was able to determine the position of the I-beam to within the accuracy of the LADAR, i.e., the uncertainty of the position was within the uncertainty of the LADAR. The algorithm was also able to correctly determine the orientation of the I-beam.

As mentioned earlier, at the time of publication of this paper, only one of the 90 data sets was examined. Uncertainties of the pose determination, and effects of point density, angle of the object relative to the scan direction, and voxel size on the pose determination will be reported in a future publication when all the data have been analyzed.

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Automatic Tunnel Monitoring System to Prevent Structural Failures & Collapses

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Abstract: Given the geographical characteristics and the national demand for sustainability, there is a strong need for tunnel construction in Korea. According to national highway construction statistics released by MOCT (Ministry of Construction and Transportation), tunnel s built after 1997 account for 54% of total number of tunnels. Up to now, measurement of position, pressure, force, torque, flow, magnetic field, temperature, humidity, gas composition, and liquid molecular concentration has relied on wired sensors regarding tunnel management. Such wired systems are exposed to many limitations in terms of accuracy of data communicati ons between sensors and main system. Therefore, a wireless automatic tunnel monitoring syste m is needed to facilitate construction and maintenance of tunnels and to ensure safety during such processes. MEMS (MicroElectroMechanical System) combined with RF(Radio Frequency)-based micro fabricated sensor which is one of the wireless sensing systems widely used medi cal and automotive industry can provide a potentially effective solution to monitor tunnel asses sment, crack detection, and tunnel construction monitoring. It has great potential in terms of applications to many areas of civil infrastructure systems along with standardization of data sensing, communication and analysis technologies. This paper presents a framework of automa tic monitoring system based on MEMS technology for on-going tunnel construction. Current application and analysis of conventional wired and MEMS based sensing technology will be included in this paper. This paper consists of sections describing: (1) Development framework of the automated tunnel sensing system (ATSS, Automated Tunnel Sensing System) (2) Analysis of current sensing methds for tunnel.

Keywords: Sensor, MEMS, Tunnel, TMS (Tunnel Management System), RF (Radio Frequency)

1. INTRODUCTION

1.1 Need for Systematic Data Acquisition

1.1.1 Construction

Regarding the national roads built and maintained by Ministry of Construction and Transportation (MOCT) in Korea, 54% of tunnels have been constructed after 1997 among all the tunnels built in the last 30 years for various reasons including environmental preservation. National highways tunnels are also on the rise, accounting for 66% of all the tunnels (as on May, 2003). However, as tunnel data monitoring is not standardized across the tunnels and measured data not managed systematically, such data is not utilized properly as basic inputs to tunnel maintenance activities.

Therefore, automation of civil structure data monitoring and systematic management of such data is required and automated, compact and wireless tunnel management system is necessary to meet the requirement.

1.1.2 Environment

Environmental concern has become the foremost factor to be considered in tunnel construction and maintenance. Notably, tunneling is one of the civil construction approaches to minimize environmental damages in mountainous regions. However, as indicated by the suspension of Sapae Mountain Tunnel construction regarding the Seoul Ring Way which incurred more than KRW 540 billion in loss, significant concerns are also raised against environmental impacts of tunnel itself.

Therefore, consideration of environmental factors during tunnel construction and maintenance is more critical than ever and it is necessary to manage environmental impacts of construction sewage, underground water leakage and exhaust emission, etc. to minimize damage to environment.

1.1.3 Maintenance

Tunnel data is measured in a limited scope for a short period of time or after cracks are detected, but, systematic data monitoring and management is required under the broader concept of Tunnel Management System (TMS).

1.2 Disadvantages of Wired Sensors

Sensors need to be utilized in a systematic manner to meet the aforementioned requirements, however, the conventional wired sensors are limited in itself in terms of installation and maintenance, exposed to more risks of damage and cost implications.

1.3 Objectives

To address the aforementioned tunnel monitoring system and sensors, two following research purposes are proposed regarding structural health for tunnels monitoring technology for structural failure prevention:

- Development of framework to combine conventional automatic sensors/RF-MEMS-based sensors & development of data management system;
- Development of framework for small wireless sensors and their applications based on RF(Radio Frequency)-MEMS(MicroElectroMechanical System) technology.

2. TUNNEL DATA MONITORING TO DATE

As for a sizable civil structure such as tunnel, management of monitored data required for construction and maintenance activities affect significantly efficiency of such activities.

Regarding tunnel data monitoring, Korea is on par with other countries as far as manual-monitoring technology is concerned, however, automatic monitoring of Korea is less developed when compared to other countries. Integral constituents of automatic monitoring technology are automatic monitoring management application and automatic monitoring sensors and imported products are used in most applications.

Table 1. Daily Data Measurement

Item	Description
Face Mapping	-Sheets, joints & fractures of face & exposed surface -Ground water leakage conditions & volume -Strain and defects of supports
Lining Strain Measurement	-Lining strain size, rate and convergence
Tunnel Arch Crown Subsidence Measurement	-Tunnel arch crown subsidence degree -Subsidence rate & convergence
Rock-bolt Pull-Out Test	-Adhesive strength of rock-bolts in place at different depth
Soil Subsidence Measurement	-Subsidence of soil over the crown of tunnel

Therefore, technologies applicable to tunnel maintenance are not properly utilized in many aspects in Korea as they should due to insufficient awareness of significance of tunnel maintenance up to now. In other countries, applicable technologies applicable to many aspects of tunnel monitoring have advanced to a significant degree, but, a system that can deliver integrated management functionality still seems in the making [1]. Following Table 1, Table 2 show recommendation on measurement items and their descriptions.

Table 2. Representative Data Measurement

Item	Description
Underground Strain Measurement	-Volume, rate and convergence of strain in semi circular area of rocks around tunnel
Rock-bolt Axial Force Measurement	-Axial force distribution, variation rate and convergence of rock-bolts in place
Shotcrete Stress Measurement	-Radial and tangential stresses, their variation rates and convergence of shotcrete in place
Underground Subsidence Measurement	-Degree of subsidence measured at tunnel floor at different depth

3. MEMS APPLICATION RESEARCH TREND

3.1 BiAST(Biaxial Strain Transducer)

BiAST is a biaxial strain sensing system applicable to rails developed by the University of Iowa based on MEMS technology[2]. The system was originally developed to monitor strain of aircraft structures, but, modified by the University of Iowa for application to rail. BiAST consists of Emitter beam, CMOS IC Chip, Connector, Sealed biaxial Mechanical flexure and Sensor base assembly, etc. integrated by MEMS technology. The system is installed at critical sensing spots to collect strain history data and identify rail fatigue conditions for maintenance.

3.2 MEMS-Based Accelerometers & Wireless Structural Monitoring System

This system was developed by the Stanford University and composed of MEMS-based accelerometers and wireless real time structural monitoring system module [3]. MEMS-based accelerometers measure acceleration based on variation of resistance in piezoresistor in reference to proof mass movement as described in Figure 1.

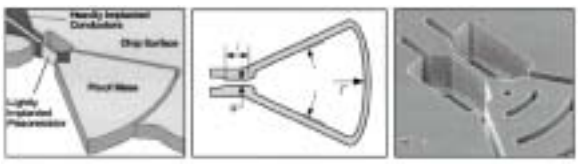

Figure 1. MEMS Based Accelerometer

4. RESEARCH RESULTS

4.1 Conceptual Design of Tunnel Monitoring System

Tunnel monitoring system consisted of conventional sensors and MEMB-based ones as described in Figure 2 is proposed to address the issues identified in the Introduction herein. In principle, the system monitors data wirelessly, whether the sensors used are conventional ones or MEMS-based ones. However, wired sensors can be used, depending on their application. Sensors are arranged per requirements of each work activity and data acquired in construction and maintenance phases is stored and managed by system. Data accumulated in the aforementioned manner can be applied to construction and maintenance activities.

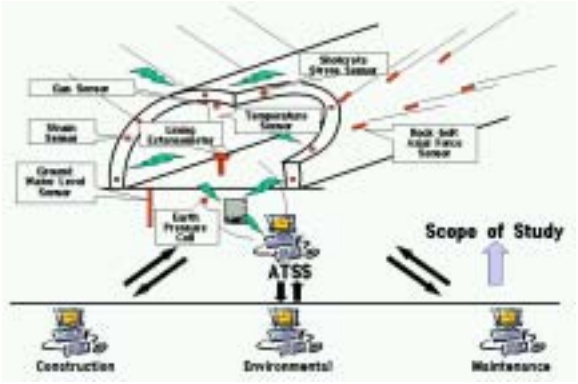

Figure 2. Concept of ATSS

As the system is a generic measurement and data management system, it can be applied to other civil structures such as bridges or dams, etc.

4.2 Selection of Target Activities

Tunnel monitoring can be divided into data measurement at in and out of tunnel body and tunnel body is broken down to tunnel body and inner tunnel parts (lining, floor and appurtenant).

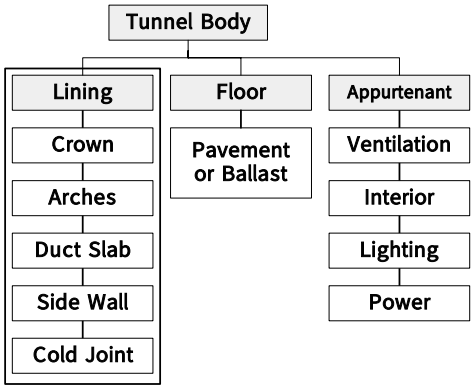

Figure 3. Targeted Activities

This research targeted crown, arch, duct, side wall and cold joints in consideration of ease of development and benefits as illustrated in Figure 3 in reference to recommendations of tunneling experts.

4.3 Development Methodology & Conceptual Design (Pending)

Referring to the achievement made by preceding researches and MEMS development methodology, development processes are proposed as described in following Figure 4. First of all, processes of the targeted activities were analyzed, required measurement items (strain or chloride etc.) were defined and targeted requirements of tunnel monitoring sensors were developed. Applicable technologies are selected as per targeted specification and subsequent processes follow in the order of design, analysis and simulation. If the design feasibility is verified in simulation, production process and mask design are defined to develop MEMS sensor.

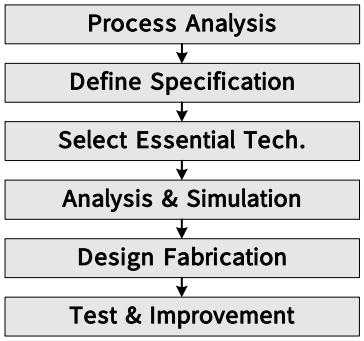

Figure 4. MEMS Development Methodology

Development of RF-MEMS sensor in accordance with the aforementioned processes require following consideration illustrated in Table 3. In development phase, sensor specification is defined in consideration of tunnel-specific environmental factors and appropriate material is selected. Regarding adoption of RF technology for wireless communication, decision should be made between passive and active types in consideration of service life of tunnel and efficiency of communication. Following sensor development, strain rate measurment spots or measured data collection interval must be determined and possibility of integrating various sensors in a single chip needs to be considered as well.

Conceptual design of MEMS sensors based on achievements made by researches available up to date is as described in Figure 5.

Table 3. RF-MEMS Sensor Development Consideration

Phase	Considerations
Development	- Tunnel-specific environmental factors - Spec.(strain rate measurement range, errors, etc.) - Selection of strain rate-measurement material
Wireless Communication	- Passive or Active (in consideration of service life of tunnel) - Maximum/optimum wireless communication-capable concrete depth
Application	- Selection of strain rate measurement spots - Strain direction measurement method - Measured data collection interval & method
Future Evolution	- Optimum combination of integratable sensors for strain rate, chloride, temperature and vibration, etc.

Sensors that can be most effective in application to tunnel body such as lining are strain rate sensors and its actuator is made from PZT most widely used and favorable in terms of its electrical and physical properties. Variation of resistance is received from actuator and data is transmitted to external antenna by Radio Frequency (RF) module after the resistance variation is analyzed. As the external antenna is more malleable than the actuator, it is expected to be safe from strain.

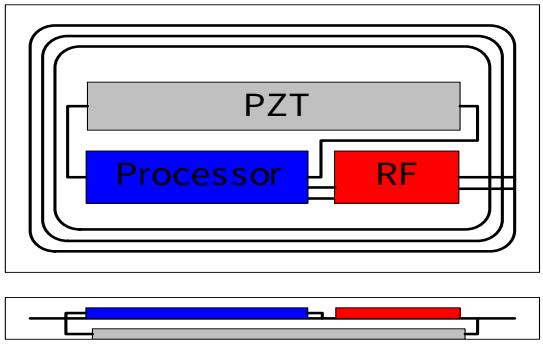

Figure 5. Concept Design of MEMS Sensor

5. CONCLUSION

ATSS targeted by this research can advance development of automatic monitoring and data management system applicable to tunnel construction, environmental preservation and maintenance and may support tunnel structure failure and advance safety planning. In addition, from economic and industrial perspectives, operation and maintenance costs are expected be saved as well as social costs since damages to civil structures can be addressed in advance, their service life extended and safety accidents prevented. Moreover, sensor markets will be expanded in the wake of MEMS sensor development and MEMS-based sensor makers will be able to advance into a market worth USD 5 billion in 2 years. Lastly, in terms of social implication, generic automatic monitoring and data management technologies can be applied to other civil structures (bridges or dams, etc.), resulting in mitigation of more safety hazards in construction industry as a whole.

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REAL-TIME ADAPTIVE COLOR SNAKE TRACKER USING CONDENSATION ALGORITHM

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Abstract: Motion tracking and object segmentation are the most fundamental and critical problems in vision tasks such as motion analysis. An active contour model, snake, was developed as a useful segmenting and tracking tool for rigid or non-rigid objects. Snake is designed on the basis of snake energies. Segmenting and tracking can be executed successfully by energy minimization. In this research, two new paradigms for segmentation and tracking are suggested. First, because the conventional method uses only intensity information, it is difficult to separate an object from its complex background. Therefore, a new energy and design schemes should be proposed for the better segmentation of objects. Second, conventional snake can be applied in situations where the change between images is small. If a fast moving object exists in successive images, conventional snake will not operate well because the moving object may have large differences in its position or shape, between successive images. Snake's nodes may also fall into the local minima in their motion to the new positions of the target object in the succeeding image. For robust tracking, the condensation algorithm was adopted to control the parameters of the proposed snake model called "*adaptive color snake model*". The effectiveness of the ACSM is verified by appropriate simulations and experiments.

Keywords: Active contours, adaptive color snake model, condensation algorithm, object tracking, image segmentation, energy minimization, optical flow, Kalman filter

1. INTRODUCTION

In recent years, automatic controls have affected the world in various fields. Automation has been carried out in factories, military, services in hospitals, and so on. The controllers of high performance need large amounts of integrated information about systems and the environment for feedback. A vision system is a sensor that is capable of giving this kind of information. Vision sensors are necessary for sensing obstacles or targets in complex systems such as mobile robots, active and intelligent cruise controls. In a vision system, processing such as segmentation and tracking are critical tasks to be accomplished satisfactorily. A considerable work has been done during the past decade in object tracking and motion analysis of nonrigid objects in the context of snake models. Active contour models have been developed as useful tools for segmenting and tracking rigid and nonrigid objects. Snake, one of the active contour models, was introduced by Kass *et al*. [1] in 1987. They defined snake energies such as internal energy, image energy and external energy. Segmentation and tracking can be done by this energy minimization process. They tried to solve optimization problem for energy minimization by use of the variational approach. They have applied snake to track facial features such as lips in an image sequence. The estimated motion parameters of these features were used to explain facial expressions, etc. Leymarie and Levine [2] have used the snake model to track cells in biological image sequences and proved the convergence of snake's motion. DeCarlo and Metaxas [3] have proposed a deformable face model which includes both shape and motion parameters and have applied it to track human faces. Point distribution based active shape models were also proposed by Kervrann and Heitz [4] to track objects in long image sequences, where a point distribution is used to characterize the structure and variations in the object shape.

Besides the object boundaries, various information in an image or a sequence of images have been used for segmenting objects. Appearance information including grayscale or color have been used in conjunction with deformable shape models [5]. Bascle and Deriche [6] have combined texture correlation of the entire internal region of the object and B-spline contour along the object boundary. Color information has also been used to track nonrigid objects in real-time application [7]. While an active contour model is applied to track an object, stepping to the next image frame in the presence of a large motion difference between them may cause unpredictable effects on the tracking contour. If the variance of the object's location and the configuration between two successive images is large due to the abrupt increase of the object's speed or the low operation speed of the vision system, then the tracking of snake cannot be guaranteed. For the better tracking performance, some advanced algorithms were employed for motion estimation in the snake

(a) *(i-1)*th frame (b) *i*th frame (c) *(i+1)*th frame

Fig. 1. Example of visual tracking; successful visual tracking involves successive segmentation of boundaries of the target object through a sequential image stream. Target object is framed in the rectangular box.

model. Optical flow algorithm has been commonly applied to estimate the object's motion [3], [8]. But, the computation of the optical flow field for the entire area of interest lead to a considerable computational complexity. It may be effective only for a static camera. As the camera moves, the system generates many variations between successive images. Optical flow-based approach is not suitable for these situations. Another approach is the Kalman filter, a powerful tool for motion analysis [9], which is an frequently used in dynamic estimations. Kalman filtering requires the system to be linear, with its observations be linear functions of the underlying state. The most obvious difficulties of the visual tracking lie in the modeling of the shape uncertainty and the probability density of the state. Most of the algorithms that use the state-space description are based on Kalman filtering. Kalman filtering has a mechanism that fuse the current noisy measurement information and the estimation based on the history of states. Kalman filtering deals with the uncertainty of the state by carrying the covariance matrices of the states and the measurements, and it works optimally when the noise is Gaussian. This indicates that Kalman filtering algorithm can fail when the uncertainty in the system has multi-modal distribution. This is exactly what happens in the noisy measurement data from an image with several visual clutter, which causes malfunction of the Kalman filter in such situations. The condensation algorithm has been employed in many researches. One of the striking properties of condensation algorithm is its simplicity compared to the Kalman filter. In presence of camera motion, the condensation algorithm shows the robust tracking of object's motion. In following sections, the condensation algorithm will be described in detail.

In this paper, we propose a new snake model, which is capable of dealing with color information. And, we also present a realtime algorithm to track and segment a moving object using the condensation algorithm for better tracking performance. In Section 1, the problem statement is discussed. Section 2 and 3 review the conventional snake and condensation algorithm. The proposed snake model, ACSM and tracking scheme are presented in Section 4 and 5. Experimental results with ACSM on a real video sequence are presented in Section 6. The conclusions are given in Section 7.

2. PROBLEM STATEMENT

Visual tracking involves successive segmentation of the target object's boundaries in a sequence of images. Figure 1 shows three sequential images for visual tracking of a particular object in them. Accurate visual tracking involves the successive segmentation of the object's boundary. Snake's segmentation process is related with energy minimization. Snake energies should be defined in such a way that include the boundary information as minimum energy states. If the minima of the energy surface is found accurately through the energy minimization process, snake can figure out the object's boundary. This is the segmentation process. When the variance of the object's location and the configuration between two successive images is small, snake can also make segmentation of the succeeding image from the contour of the preceding image through the process of energy minimization. This is the tracking process of snake. When the variance between successive images is small, Kass' snake operates well by the variational solution or dynamic programming method. But in the case of large variance between successive image streams, the convergence of snake motion cannot be guaranteed as the assumptions of variational approach is not effective in such situations. This is a major problem of snake in objects tracking, which may have discrete motions in image streams due to the abrupt increase of object's speed or the low performance of the vision system. Furthermore, when the object moves in a complex background, using only image intensity information is not enough to separate the object from its background. This is another major problem of snake in segmenting objects.

3. BRIEF REVIEW OF CONVENTIONAL SNAKE

Kass introduced snake concept in 1987, where he proposed a contour, a deformable curve, and its energies and solutions based on variational approach. Consider a deformable curve *v(s,t)* with parameters *s* (spatial index) and *t* (time index), defined in given open intervals Ω and T, where it is a function of two variables *x* and *y* with the parameterization

$$v(s,t) = (x(s,t), y(s,t)); \quad s \in \Omega, t \in T \tag{1}$$

Kass defined energy terms, that are functions of the contour *v(s,t)*.

Active contour models are the energy-minimizing spline guided by internal constraint forces and influenced by external image forces that pull it toward features such as lines and edges. The conventional energy function in the snake is defined in discrete form as follows:

$$E_{snake} = \sum_{i=1}^{n} [E_{int}(i) + E_{image}(i)], \tag{2}$$

where *n* is the number of snake node (called *snaxel,*

v_i), the internal spline energy $E_{int}(i)$, and the external image energy $E_{image}(i)$, at the ith position of the contour, are described as

$$E_{int}(i) = \alpha_i |v_i - v_{i-1}|^2 + \beta_i |v_{i-1} - 2 \cdot v_i + v_{i+1}|^2 \quad (3)$$

$$E_{image}(i) = -|\nabla f(v_i)|^2 \quad (4)$$

where $f(v_i)$ is the original pixel value at v_i. The symbols α_i and β_i are the weighting factors. The image energy is set to be the negative magnitude of the image gradient, so that the snake is attracted to the regions with low image energy, i.e., strong edges. Thus a snake model is actually a function with a compromise balance between internal and image forces.

4. CONDENSATION ALGORITHM

The condensation algorithm has attracted much interest in the field of active vision as it offers a framework for dynamic state estimation, where the underlying probability density function is not required to be Gaussian. The algorithm is based on factored sampling but extended to apply iteratively to successive images in a sequence. As new information becomes available, the posterior distribution of the state variables is updated by recursively propagating these samples.

The state of the modelled object at time t is denoted by $x_t \in R^n$, where as its history is denoted by $X_t = \{x_1, \ldots, x_t\}$. Assuming that the exact state is not known, we describe the knowledge about an object by a probability function $p(x)$.

Similarly the measurement of the object at time t is $z_t \in R^n$. with history $Zt = \{z_1, \ldots, z_t\}$.

A general assumption is made for the probabilistic framework that the object dynamics form a temporal *Markov process* so that

$$p(\mathbf{x}_t | \mathbf{X}_{t-1}) = p(\mathbf{x}_t | \mathbf{x}_{t-1}). \quad (5)$$

The density function $p(x_t)$ depends only on the immediately preceding distribution $p(x_{t-1})$, but not on any function prior to t-1.

The condensation algorithm describes the sample-based representation of the recursive Bayesian filter and applies factored sampling iteratively to calculate $p(x_t|Z_t)$. We always have a sampled distribution $p(x_t|Z_{t-1})$, thus, the initial creation of a sample set can be omitted.

An iteration step of the condensation algorithm starts with a sample set s representing $p(x_{t-1}|Z_{t-1})$ from the previous time step. We propagate s to obtain a new sample set s' according to the system model so that s' represents $p(x_t|Z_{t-1})$. Applying factored sampling, a set s" is drawn from s', where each element of the new set is chosen with a probability $p(z_t|x_t)$ so that s" represents the new *a posteriori* density $p(x_t|Z_t)$.

5. ADAPTIVE COLOR SNAKE MODEL

Conventional snake has proved to be a very attractive and an efficient method. Although conventional snake provides good results for slow varying object boundaries, it is not suitable for complex situations, where fast motion or abrupt variations of object contours are encountered.

The critical disadvantage of conventional snake is not to utilize the prior knowledge such as color and motion information, which often plays an important role in improving the detection performance in the presence of some disturbing image features (e.g. shadows, shading and neighboring objects). Therefore, our attention is directed towards the use of color and motion information. This consideration provides more accurate results compared to conventional algorithms, in which objects are tracked by exploiting motion information; this is more evident in sequences with complicated content, such as fast motions, complex backgrounds, special camera effects (zooming, pantilting), etc.

Approach of ACSM is somewhat different from other approaches that utilize the color information in active contours. Most previous work has been based on the gradient of color intensity, in that a mere extension on gradient of gray image intensity is used. ACSM doesn't depend on gradient of color intensity, but it depends on the stochastic matching degree of color.

5.1 Design of energy for ACSM

We have proposed *color snake model* in previous work. The main idea was the redesign of the snake node, which can deal with color information. But, snaxels in previous research could not adapt color variations. In this paper, we propose a new formulation for ACSM.

The energy functions for ACSM are modified from the conventional snake. As shown in Fig. 2, we have designed a snaxel having two components: outside and inside color patch. These components are compared to the original image where each snaxel lays. This makes the feature/object segmentation process faster and more accurate. The newly proposed energy function is as follows:

$$E_{acs} = \sum_{i=1}^{n} [E_{int}(i) + E_{image}(i) + E_{cs}(i)] \quad (6)$$

$$E_{cs}(i) = -\sum_{k=1}^{n_{p_1}+n_{p_2}} \{W(p_{i,k}) \cdot D(p_{i,k})\} \quad (7)$$

where

$$W(p_k) = \begin{cases} \begin{bmatrix} w_1 & w_2 \\ w_2 & w_1 \end{bmatrix} & \text{if } p_k \in P_{in} \\ & \text{if } p_k \in P_{out} \end{cases}$$

$$D(p_k) = \begin{bmatrix} N(z_{p_k}; \bar{z}_{P_i}, \Sigma_1^2) N(\bar{z}_{P_i}; \bar{z}_{P_{i,gen}}, \Sigma_{1,gen}^2) \\ N(z_{p_k}; \bar{z}_{P_o}, \Sigma_2^2) N(\bar{z}_{P_o}; \bar{z}_{P_{o,gen}}, \Sigma_{2,gen}^2) \end{bmatrix}.$$

In $W(.)$, w_1 and w_2 are the user-determined weighting factors for each patch of the snake node. And, a color distribution $N(.)$ can be represented by a Gaussian distribution model as follows:

$$N(z; \bar{z}, \Sigma^2) = \frac{1}{\sqrt{2\pi\Sigma}} \exp\left(-[z - \bar{z}]^T \Sigma^{-2} [z - \bar{z}]/2\right) \quad (8)$$

where $z = \begin{bmatrix} r & g \end{bmatrix}^T$, $\bar{z} = \frac{1}{n_{p1}+n_{p2}} \sum_{i=1}^{n_{p1}+n_{p2}} \begin{bmatrix} r_i & g_i \end{bmatrix}^T$, $\Sigma = \begin{bmatrix} \sigma_{rr} & \sigma_{rg} \\ \sigma_{gr} & \sigma_{gg} \end{bmatrix}$, and *r, g* are the normalized color values.

The proposed energy function is composed of three components. First and second terms of (6) are identical to the corresponding terms in the conventional snake model. The first term is the internal energy, its modification will be mentioned in the next section. Third term is the color-fitting term so that ACSM is capable of shrinking until the contour of snake meets the desired color boundary.

In (7), the distribution of general color $N(\bar{z}_i; \bar{z}_{i,gen}, \sum^2_{i,gen})$ was multiplied to the distribution of each color, to prevent the color model from moving too far from the general color.

5.2 Color adaptation

Most color-based systems are sensitive to change in viewing environment. In general, the color representation of an object viewed with a color camera is influenced by many parameters: ambient light, object movement etc. There are two groups of researches that address environment changes: adaptation and toleration. The adaptive approach provides an alternative to making a color model useful in a large range. Instead of emphasizing the recovery of the spectral properties of light sources and surfaces that combine to produce the reflected lights, the goal of adaptation is to transform the previously developed color model into the new environment. We have adopted a method to adapt the color model. Based on the identification of the desired color histogram, the modified parameters of the model can be computed according to the following process.

In (8), $\bar{z}$ is so noisy that we use the adaptation scheme for determining the color value. Each adapted color value is determined as follows:

$$(\hat{\bar{r}}_k, \hat{\bar{g}}_k, \hat{\Sigma}_k) = \sum_{i=0}^{m-1} (\alpha_{k-i}\bar{r}_{k-i}, \beta_{k-i}\bar{g}_{k-i}, \gamma_{k-i}\Sigma_{k-i}) \quad (9)$$

where α, β, and γ are scale factors for updating each color.

5.3 Operation Flow of ACSM

The procedure of ACSM is summarized as the following pseudocode.

begin
$t \rightarrow 0$ // **t: number of iteration**
assign manually general color value $\bar{z}_{general}, \Sigma_{general}$
initialize snake node and set initial adaptation color $\bar{z} = \bar{z}_{general}$
while (not termination condition) do
    $t \rightarrow t+1$
    compute energy function using the greedy method
    find and move to the point with minimum energy
    calculate $\bar{z}$ **from the color value within patches**
    update $\hat{\bar{r}}_k, \hat{\bar{g}}_k, \hat{\Sigma}_k$
end

6. EXPERIMENTAL RESULTS

6.1 System setup

We demonstrated the performance of ACSM by applying it to real image sequences. We have implemented the proposed algorithm on a Pentium-IV 2.4 GHz PC with 512MB RAM, and a Logitech QuickCam-Pro USB camera. Three sequential images were captured at the rate of 10 frames/sec. Each image has the resolution of 320_240 pixels and depth of 24-bit color. For simplicity of comparison, 16 snaxels were used for each snake model. For ACSM, initial color distribution of the object was manually assigned. In most object tracking problems, the appearance properties (especially, color information) of target object are known. In the following experiments, however, the color information for outside patch of ACSM are not known, and therefore the energy for outside patch is not required to be calculated. Thus, only inside energy of E_{cs} in (7) is used for experiments. From the second frame, newly adapted color is applied to ACSM. The size of snake patches are 5 pixels each, along the same and opposite directions of the estimated center, which is calculated using the condensation algorithm.

The state vector for Condensation algorithm has the following form:

$$\mathbf{x}_t = [x_t \ \dot{x}_t \ y_t \ \dot{y}_t \ r_t \ \dot{r}_t \ g_t \ \dot{g}_t]^T \quad (10)$$

where (*x, y*) locates the center of the object, *r* and *g* are the normalized color of the object. In the experiments, 100 samples were used at each iteration.

6.2 Experimental results

Experiments were performed on two cases. First experiment was carried out to test the proposed algorithm for segmenting a fast moving object on a complex background. In the second experiment, the performance was tested in the presence of camera motion. To demonstrate the performance, ACSM was compared with a conventional snake, and a snake with optical flow. Through the experiments, the effectiveness of ACSM was verified.

Case 1: Large motion variance and complex background

The performance of segmentation and tracking in the case of a fast moving object on a complex background is evaluated. Experiments showed that the color information is also essential for object tracking using active contours.

As shown in Fig. 3 and 4, the target object moves across other objects, which are of different colors. Background objects with black color are used, because color difference between background object and the floor is larger than that between target object and the floor, or between target object and background objects. In this experiment, target object moves forward and rotates considerably.

(a) frame 3 (b) frame 7 (c) frame 11 (d) frame 15

Fig. 3. Experimental results for conventional snake with optical flow in case 1.

(a) frame 3 (b) frame 7 (c) frame 11 (d) frame 15

Fig. 4. Experimental results for ACSM in case 1.

(a) frame 5 (b) frame 9 (c) frame 13 (d) frame 17

Fig. 5. Experimental results for ACSM in case 2.

Figure 3 shows the results of conventional snake with motion information using optical flow. From frame 1 to 5, conventional snake works well. But, target object encounters background objects with larger edge intensity from frame 6. Since edge intensity of the background object is larger than that of the target object, snaxels tend to be attracted to the boundary of the background object.

Figure 4 presents the results of ACSM. In contrast to results of the conventional snake, ACSM is capable of tracking an object more accurately, since color information of the object is also used. Though the background object with high edge intensity is located near the target object, E_{cs} in (7) attracts snaxels to the object's boundary.

Case 2: With camera motion

Second experiment was carried out in order to show the capability of ACSM in real-time tracking while the camera is in motion. The computation of the optical flow field for the entire area of interest requires considerable computational complexity. Thus, it may be effective only for a static camera. As the camera moves, the system generates considerable variation between two successive images. Therefore, optical flow-based approaches to real-time tracking system need longer calculation time. Therefore, in case 2, conventional snake with optical flow fails to operate in real-time at frame rate of 10 frame/sec as shown Table II.

We have tested the effectiveness of ACSM on a moving camera system. We have implemented the proposed algorithm on a typical pan-tilt camera system. Tracking and segmentation was performed from frame 1 to 17. Figure 5 presents the results of ACSM. With the color information of the object, ACSM has accurately segmented the object. The condensation algorithm has not been affected by the camera motion. It only considers the probabilistic distribution of desired color information.

6.3 Discussion

In this section, two considerations are described to evaluate the performance of ACSM compared to other approaches. Those are segmentation error and calculation time. In real-time application, those are the most important factors.

1) Remarks on segmentation error: For comparing with other approaches, two kinds of error measure are accepted as measure for segmentation error. Following measures are the gauge to the accuracy of segmentation. First error measure is given as follows:

$$E_{SCB} = \frac{SCB(n)}{n} \tag{11}$$

where n is the number of snaxels, and $SCB(.)$ refers to the number of snaxels on the correct boundary. This measure converges to 100% when correct segmentation is done. Second segmentation error is given by

$$E_{card} = \frac{card(T \cap B^c) + card(T^c \cap B)}{card(T)}, \tag{12}$$

where T is the target object mask, B is the background object mask, and $card(.)$ is the the cardinality (i.e., number of pixels) of a set.

Table I shows the comparison between conventional snake and ACSM. In order to compare on the same condition, condensation algorithm for tracking

method and 50 nodes for snaxels were used to evaluate measures on each frame. And, same initial positions for snaxels were used at each frame. Table I says that ACSM is less disturbed than the conventional method, in the presence of background object with high edge intensity and camera motion.

TABLE I
RESULTS OF SEGMENTATION ERROR

Case	Segmentation method	E_{SCB} (%)	E_{card} (%)
Case 1	Conventional snake	70.70	69.31
	ACSM	98.58	3.29
Case 2	Conventional snake	63.02	115.85
	ACSM	98.23	2.94

2) Remarks on calculation time: In real-time systems, calculation time for the proposed algorithm is of great importance. The computational burden in the real-time implementation of the algorithm for object tracking system is the motion estimation. For the better performance of tracking, several advanced algorithms for motion estimation has been employed in the snake model. Optical flow algorithm has been applied to estimate the object's motion. But, the computation of the optical flow field for the entire area of interest requires considerable computational complexity. It may be only effective for a static camera. As the camera moves, the system generates a considerable variation between two successive images. In presence of camera motion, Condensation algorithm shows the robust tracking of object's motion.

Table II shows the average calculation time for processing each frame. This table includes the comparison between tracking methods: optical flow and condensation algorithm. As shown in case 1 and 2, in the case of considerably rotating object or camera motion, calculation time for extracting motion vector is too large to operate in real-time. But, ACSM with condensation algorithm is suitable for real-time application.

TABLE II
RESULTS OF CALCULATION TIME

Case	Segmentation method	Tracking method	Time (ms/frame)
Case 1	ACSM	Optical flow	157
	ACSM	Condensation	89
Case 2	ACSM	Optical flow	373
	ACSM	Condensation	94

8. CONCLUSION

In this paper, we have introduced a real-time object tracking scheme using a new snake model, called "*adaptive color snake model* (ACSM)" which can be applied to color image segmentation and object tracking. Through experiments, the effectiveness of the proposed algorithm was verified.

Experimental results show the potential of the proposed ACSM and tracking scheme. Despite the fast motion, complex background, special camera effects, ACSM can also operate in real time. Therefore, proposed tracking scheme is more suitable than intensity-based or optical flow-based approaches.

Acknowledgments

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Human-Assisted 3D Spatial Modeling of Construction Sites Using Sparse Range-Point Clouds

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Abstract: 3D spatial-modeling can be used in various safety-enhancement applications and for as-built data acquisition in project-control systems. The objective of the research reported herein was to provide spatial-modeling methods that represent construction sites in an efficient manner and to validate the proposed methods by testing them in an actual construction environment. Algorithms to construct construction-site scenes and to carry out coordinate transformations in order to merge data from different acquisition locations are presented. Field experiments were conducted to establish performance parameters and validation for the proposed methods and models. Initial experimental work has demonstrated the feasibility of this approach.

Keywords: Sparse range-point cloud, 3D spatial-modeling, convex hull, workspace partitioning

1. INTRODUCTION

The dynamic nature of the construction environment requires not only that a real-time local-area modeling system be fast but also that it be capable of dealing with uncertainty and adjusting to changes in the work environment. The ability to cope with uncertainty is very important and is being recognized as the next logical step in the robotics field as well.

3D spatial-modeling methods that are currently in use, including 3D CAD and dense 3D scanning systems, have certain limitations, in that they are time consuming and labor intensive and require high performance computers. Models generated by 3D CAD system are very accurate, but the process is extremely time-consuming, primarily because of the time needed to make the measurements, which is done manually. In many cases, drawings of the site are not obtainable or do not match the as-built conditions. Furthermore, as modifications are made to the site—or equipment is added or moved around—many additional hours may be needed to construct a model of the site. These problems are exacerbated if data cannot be gathered because access to the facility is limited—on account of environmental conditions, such as the presence of safety hazards, or because the area is already occupied. For construction and maintenance of infrastructure, generation of a detailed, accurate model is not all that critical. In most cases, a collection of simple, primitive shapes will suffice (in fact, this is often the preferred approach).

There are major problems associated with dense 3D scanning systems that generate high-quality polygonal meshes from coordinate data for a set of scattered points [2]. Data obtained from laser scanning systems tend to be rather noisy and to contain errors that render most segmentation and modeling algorithms inadequate. The reconstruction of surfaces from unorganized point clouds derived from data obtained with a laser scanner is a very hard problem that has not yet been completely solved—and is especially problematic in cases where the data are incomplete, noisy, and/or sparse [11]. The process of converting an unstructured point cloud that represents the local geometry into a consistent polygonal model often requires days or even weeks [9], and typically consists of four steps: pre-processing, determination of the global topology of the object's surface, generation of the polygonal surface, and post-processing [4]. Because these point clouds can consist of millions—or even tens of millions—of sampled points, use of such a conversion process is mandatory in order to reduce the input complexity while maintaining a desired proximity [4]. The outcome is often far from ideal, however, since in many cases the 3D models created from the scans are still so large that even a high powered computer could be hard pressed to display the data in real time [10].

A recent study by Jaselskis et al. shows that laser scanning systems are not adequate for use in applications requiring high accuracy, such as in the measurement of the smoothness of asphalt surfaces [6]. The data they have compiled show that use of currently available laser scanning technology in real-time applications is problematic, on account of the long processing time required. Also, this study points up some drawbacks in the technology insofar as data acquisition and data processing are concerned.

The aim of the research described herein is to develop a 3D spatial-modeling method that uses bounding algorithms, including a workspace-partitioning algorithm and an algorithm for constructing a convex hull, and to investigate how well the workspace modeling approach suggested herein succeeds in the representation of construction sites by running experiments in actual construction environments.

2. SPARSE RANGE-POINT CLOUD APPROACH

While the dense point cloud methods including dense 3D scanning systems can produce very detailed models of the scanned scenes, which are useful for obtaining as-built drawings of existing structures, the burdens that they impose in terms of computation and data-acquisition time generally preclude the use of these types of laser systems for on-site, real-time decision-making. Modeling times for these laser range scanners can be on the order of hours or even days. In addition, it is virtually impossible to perform automated path planning based on their output, because of the exorbitant computational cost of considering each point of a surface in the vicinity of the equipment being used for a given task [5]. Despite certain disadvantages in using dense, 3D laser scanning, such as the lack of traceability, the high cost and large size of the equipment that is required, and the length of time needed for the processing phase [14], the most significant feature of any dense, 3D laser scanning system is its near-real-time capability to track moving objects or people.

In contrast to full-area, "dense", range-point scanning, the use of sparse point cloud requires times on the order of only minutes or seconds for data acquisition and 3D modeling. Moreover, humans are adept at recognizing objects, especially in cluttered scenes such as construction sites [7], so by incorporating human perception into the overall modeling enterprise, an objective-driven, sparse point cloud approach has the potential to reduce not only the data-acquisition time but also the need for computationally intensive and/or expensive processing [3, 12].

Another characteristic of the sparse range-point cloud approach is the use of geometric primitives. Such geometric forms are ideal for modeling construction environments, since they require very little memory, even for large world maps, and they are easy to store and manipulate [11]. They can be ideal for modeling construction environments as well, since they require very little memory, even for large world maps, and they are easy to store and manipulate. In fact, the availability of a detailed local model to represent a construction-site scene is not critical. In applications that entail real-time obstacle avoidance, for example, the use of geometric primitives often suffices.

3. HUMAN-ASSISTED SPATIAL-MODELING

3.1 Process of human-assisted spatial-modeling

The process used in the spatial-modeling described herein is outlined in the flowchart in figure 1.

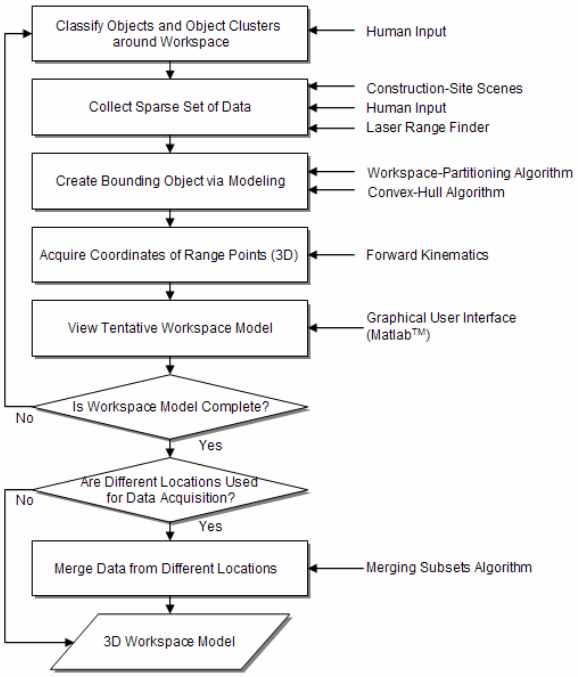


Figure 1. Flowchart of human-assisted spatial-modeling process

To acquire the spatial-information, humans first classify objects in and around the workspace and collect the range-point data that have been acquired with an inexpensive, single-axis, laser rangefinder mounted on a pan-and-tilt unit. Through the use of two general classes of geometric primitives (convex hulls and workspace partitions), bounding objects representing a wide range of construction-site scenes are created. Where more precise geometric primitives are required, object fitting and matching method can be incorporated, but it is not used here fore the sake of clarity. In cases where the operator's view from any one reference point is limited and the coordinate data have to be acquired from two or more locations, the subsets of range points obtained from the different locations are merged into a single set before the site model is generated.

3.2 Algorithms for human-assisted spatial modeling

Given the types of objects most frequently encountered on a construction site, a wide range of

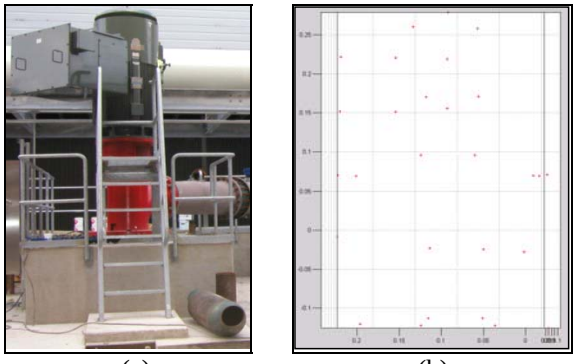
construction scenes can be modeled by use of just a few classes of geometric primitives. Convex hulls and workspace partitioning are promising candidates for tools that can be used in modeling construction-site scenes. Convex hulls can be employed in the representation of a wide range of construction-site scenes, such as pipe racks, building structures, and other types of equipment, while workspace partitioning can be used to delimit workspaces.

Descriptions of algorithms for convex hull and workspace partitioning are given below, followed by an explanation of the coordinate transformation which is needed for merging data that are acquired at different locations.

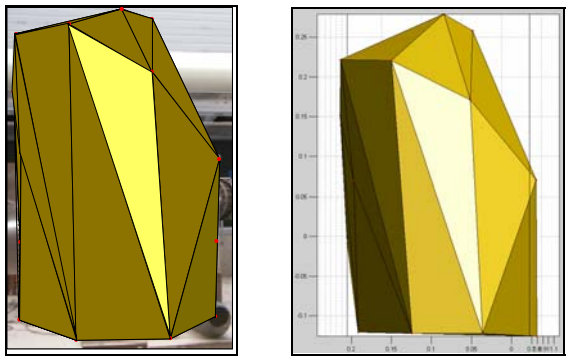
3.2.1 Convex hulls

In three-dimensional space, the convex hull of a set of points is the smallest convex volume that contains those points [1]. For the following reasons, the use of convex hulls is well suited to rapid spatial-modeling: (1) such volumes are inherently conservative, because of their convex nature, (2) any number of points can be picked, anywhere, and (3) the resulting hull is bounded by planar faces, thereby enabling rapid computation of distances [13].

The algorithm chosen for use in the research described herein is an incremental algorithm by Barber, Dobkin, and Huhdanpaa which adds just one point at a time to the convex hull generated from the entire set of points processed during earlier steps of the procedure [1]. The algorithm consists of three parts: initialization, partitioning, and iteration. A detailed description of the convex hull algorithm is given the article by Barber et al. An example of the convex hull modeling process is displayed in figure 2.



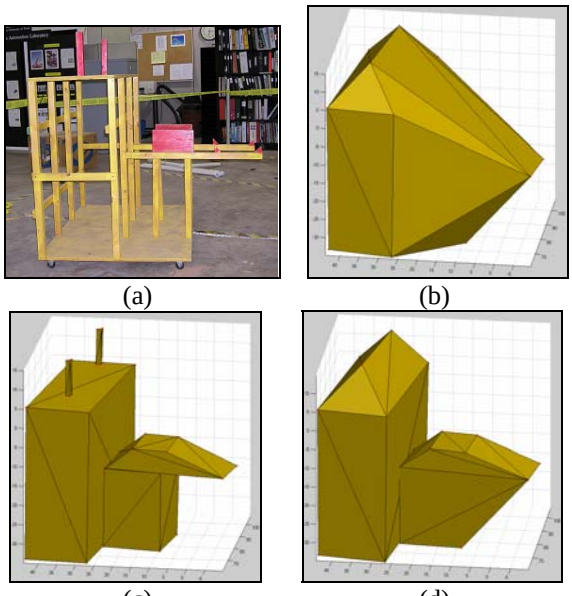
(a) (b)



(c) (d)

Figure 2. Convex hull modeling: (a) picture of actual object to be modeled, (b) scanned range points, (c) bounding object, (d) resulting convex hull

One of the benefits of using a convex hull algorithm in generating world models is that the user can set the level of accuracy of the model in accordance with their particular requirements. In the case of the pipe rack shown in figure 3 (a), three different models were generated: one that used a single convex hull (figure 3 (b)), one that was obtained by using two convex hulls (figure 3 (c)), and one that employed five convex hulls (figure 3 (d)). Clearly, the latter two models represent the object more accurately than the first model.



(a) (b)

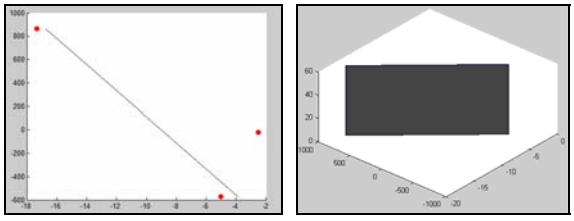
(c) (d)

Figure 3. Variation in accuracy of models with number of convex hulls: (a) picture of actual object to be modeled, (b) model generated from one convex hull (c) model generated from two convex hulls, (d) model generated from five convex hulls

3.2.2 Workspace partitioning

An earlier research effort at the University of Texas at Austin proposed that a finite plane (or extremely thin wall) be used for partitioning a workspace (McLaughlin et al., 2004). Geometrically speaking,

any set of three non-collinear points suffices to define a plane. However, application of a least-squares approach that uses more than three points, to ensure that the plane is placed where the operator intends it to be, is often a better way to proceed. The simple plane model is very useful for quickly partitioning a scene. Floors, walls, and ceilings can easily be modeled by picking a few additional points. Safety-driven applications can easily be envisaged, such as a backhoe being operated next to a busy city street; in this scenario, a wall would act as a partition between the operator's workspace and the forbidden zone of the street. A detailed description of the workspace-partitioning algorithm is given in [12]. An example of the workspace-partioning algorithm is shown in figure 4.



(a) (b)

Figure 4: (a) scanned points and results of least-squares method (b) results of workspace partitioning

3.2.3 Merging model subsets from different locations

Because an equipment operator's view from any one reference point can be limited, multiple sets of range data may need to be used in modeling a workspace. Each set of range points is acquired at a different location, which serves as the origin of a coordinate system for that set of data. Since the range points from all the sets must be merged in order to model the workspace, their coordinates must ultimately be given with respect to a common coordinate system. The transformation is used to convert the components of a position vector from one coordinate system to another. Detail description of transformation is given in [8].

3.3 Data Acquisition Setup for Spatial Modeling

The coordinates of range points for various types of objects are acquired in three dimensions by using a laser with pan-and-tilt kinematics. The equipment used for data acquisition and modeling consists of 1) a laser rangefinder, 2) a two-axis pan-and-tilt unit (PTU), 3) the laser manufacturer's distance-data-acquisition software, 4) a tripod, 5) a C program that continuously reads pan and tilt angles from the PTU, and 6) modeling routines developed in Matlab™ that display the models graphically via a graphical user interface (GUI). The hardware setup is portrayed in figure 5.

Figure 5. Hardware system

3.4 Graphical user interface for data acquisition

The proposed modeling system requires that the operator run various computer programs (such as the laser manufacturer's distance-data-acquisition software, the pan-and tilt-unit program, and the Matlab graphing program) in order to acquire the range data. For a computer novice, this can be quite challenging; indeed, it is rather cumbersome even for an expert.

In the system described herein, a graphical user interface (GUI) enables the equipment operator to acquire data much more readily. The GUI was designed with an option-menu display to enhance the efficiency of data gathering by the operator (Figure 6).

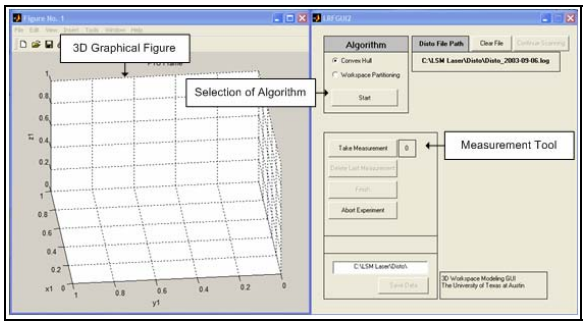


Figure 6. Graphical user interface

4. EXPERIMENTS IN SPATIAL-MODELING OF CONSTRUCTION SITE

An investigation of how well the modeling procedures described herein succeed in representing construction sites was carried out. An experiment on spatial-modeling of construction site was conducted. The site that was modeled is the cooling-tower construction site at the University of Texas at Austin was used as a test bed for the site modeling (figure 7). During the construction, a piece of equipment known as a heavy-lift was being used to lift pipes to the top

of the object under construction.

Figure 7. Construction-site scene

This construction site, which is the workspace zone itself, is very narrow, so an equipment operator would need to exercise extreme caution in order to avoid obstacles and prevent accidents. This is a site on which safety of operation definitely cannot be guaranteed. In such an environment, an on-site spatial model could be useful, either to provide interactive visual feedback while a piece of heavy equipment is being operated or as a tool for 3D graphical simulation.

The construction-site scene was modeled using convex hulls and workspace partitioning. By use of a laser rangefinder, a few range points were selected for each object. During the object modeling, the time was measured (beginning with the registration of the first laser measurement and ending with the registration of the final laser measurement). Depending on the level of accuracy and complexity, it took anywhere from 15 seconds to about 2 minutes per object to collect the points, and less than 5 minutes to construct a model of the site scene. The results of spatial-modeling are shown in figure 8 and 9.

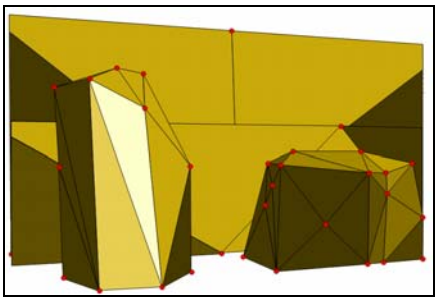


Figure 8. Results of spatial-modeling

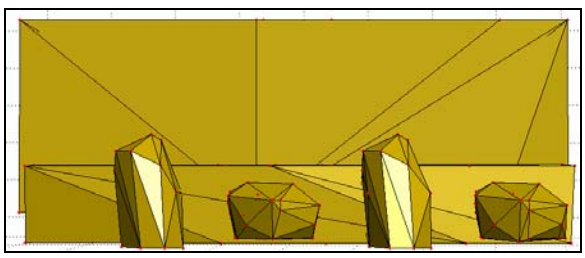


Figure 9. Results of spatial-modeling

5. CONCLUSIONS

The proposed spatial-modeling technique using convex hulls and workspace partitioning was devised and tested in actual construction environments. The algorithms used in this approach are computationally efficient and fast enough to be applied to safety enhancement in machine control, and it is also suitable for as-built applications.

Various applications of the proposed modeling methods are being developed. An obstacle-avoidance system using the proposed 3D modeling approach appears especially promising because of the fast and efficient nature of the modeling; this system is already in the simulation stage. Also, 3D spatial - modeling with the use of a bounding model is expected to see effective use in a broad class of construction automation systems.

This research will eventually be extended to combine the sparse point cloud approach with the flash LADAR dense cloud approach to make up for some of the limitations of the former, such as in the representation of moving objects (including people), though such a combined system cannot be used for modeling per se. The possibility of using flash LADAR in conjunction with sparse range-point clouds is being studied.

Acknowledgements

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IMPLEMENTATION INFORMATION TECHNOLOGY IN THE NUCLEAR POWER PLANT (NPP) CONSTRUCTION

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Abstract: Nuclear Power Plant (NPP) Construction is a long-term project with huge scales of construction data and it requires a large number of materials, labor and equipment. Also it is a grand scale project that invested with billions to build a major power supply system. To effective manage NPP construction project, it is essential to cooperate with each entities such as owner, contractor, subcontractor and regulatory agency, etc. Therefore, it is necessary to implement an information system that can be improved productivity through collaboration among construction companies and business processes in the NPP construction. By implementing information technology during project (distribution and management, pursuing integration and interfacing information with other contractors), each stage has been developed segmental information technologies. Implementing a total project management system in NPP is a key element in this paper. Therefore, the purpose of this paper is introducing an integrated information technology system for NPP. Actual examples will be given from the Uljin Nuclear Power Project.

Keywords: Nuclear Power Plant, Project Management, Information Technology

1 INTRODUCTION

Nuclear power plants (NPP) generate about 40% of electrical energy in Korea. It is a very high value compare with other countries because Korea does not have heat sources such as oil, gas, and falling water. That is the reason that Korea does concern NPP to produce electricity. Recently, 16th NPP is operating and other six NPPs are on construction in Korea. A NPP construction is a great scale project that has about 5 billion dollars construction costs and also 120 months construction schedule. Good project controls not only include planning, scheduling, estimating and cost control but also coordination of information and services. By implementing information technology during project (distribution and management, pursuing integration and interfacing information with other contractors), each stage has been developed segmental information technologies since 1990's. Thus, NPP has made a great success with developing and adjusting unit system such as designing, scheduling, cost, material, data management system by each construction level. However, due to the lack of information sharing system with other fields like business, finance and material, there was a limitation to optimize the whole corporate.

According to developing information technology, domestic NPP especially Uljin 5&6 has been tried combining between project management process and information technology. Implementing a total project management system in NPP is a key element in this paper. Therefore, the purpose of this paper is introducing an integrated information technology system for NPP especially Uljin 5&6 for actual case.

2. NUCLEAR POWER PLANT

2.1 Characteristics on the Project Management View Point

Nuclear Power Plant (NPP) Construction is a long-term project and requires huge scales of construction data, materials, labor, and equipment. Also it is a grand scale project invested with billions to build a major power supply system. To manage NPP construction project effectively, it is essential to cooperate with each entities such as owner, contractor, subcontractor and regulatory agencies, etc. It is also important issues for establishing and operating the system that can be explained by communication with various construction companies, standard regulations, and procedures such as corresponding letters, project identification systems and project management procedures.

To assist these operations in assessing the overall status of the plant, well organized project management is necessity. Thus, the view point of project management, it can be described into five characteristics in NPP. 1) long-term mega project usually 10 years from general planning, 2) generates enormous quantities of data such as quality documents, drawings and data so on, 3) great distance between data producer and user, 4) information that delivered and shared in a short time, and 5) sensibility environmental changes at organization and cooperative work system.

2.2 Project Management System

It is common that for the effective construction project, procedures and management system are kept

according to business characteristic after considering site characteristics, design, contract, and construction method. However, for the NPP construction, which requires accumulate improvement in productivity and experience in construction systematically, standardized business management systems is needed. It can be divided into organization, procedure, information, and identification system. <Table 1>

Table 1. Project Management System

System	Contents
Project related Entities	- Design, Procurement, Construction Unit (Head office and site) - Owner, A/E, Equipment supplier, Construction contractor
Project Management Procedure	- Project Procedures and Manual (PPM), Procedure manual for construction progress, Construction cost, Material, Data - Site Internal Procedure manual (SIP), Operation and quality procedure
Information System	- Server, OS, Network, Database, Application program - System design document, User manual
Project Identification System (PIS)	- Physical classification of building and system: PBS - Functional classification of plan/ data and type of construction: FBS

2.3 Work Breakdown Structure

To manage the complexity of NPP, structure breakdown is one of the most important works. The structure that various works cohered organically and segmented is called WBS, and this classifies all the construction works into top-down hierarchy.
It is segmented and systemized up to the level that planning and control management can be carried effectively. WBS can be applied identification of work and definition, defining responsibilities for work achievement, identification of minimum working unit, integration of cost and scheduling management, and so on. <Table 2>

2.4 Project Identification System

This system also greatly assisted integration, not only of documents, but also engineering and subsequent procurement, construction, and startup activities. NPP utilize a system that combined a physical breakdown structure (PBS) with an organizational breakdown structure (OBS) and a functional breakdown structure (FBS). The result is a basic number that could identify any drawing, component, cost account, schedule activity, or other product with its appropriate location or system. The common identification system became a common language.

Table 2. Nuclear Power Plant Construction WBS

Level 1	Level 2	Level 3	Level 4	Level 5	Process Rate(%) Cost[C]	Weighted Process Rate		Items
SKN1,2					%, C			Shin-Gori1,2
	C				%, C	100%		Capital Cost
		PRE			%	2%		Project Preparation
		ENG			%, C	8%		Design
		PRO			%, C	27%		Purchasing
			NSSS		%, C		10%	Installation of Reactor
			TG		%, C		4%	Turbine Generator
			BOP	A,C,..	%, C		13%	Auxiliary Equipment
		CON			%, C	58%		Construction
			CP	A1,C1,..	%, C		54%	Main Installation
			CX		%, C			Separate Order
			CY		%, C		4%	Collateral Installation
		STU			%, C	5%		Commissioning
		SUP			C			Labor Cost
		OWN			C			Owner's Cost
	F				C			Fuel

3. INTEGRATED INFORMATION SYSTEM FOR NPP

3.1 The Necessity of Integrated Information System

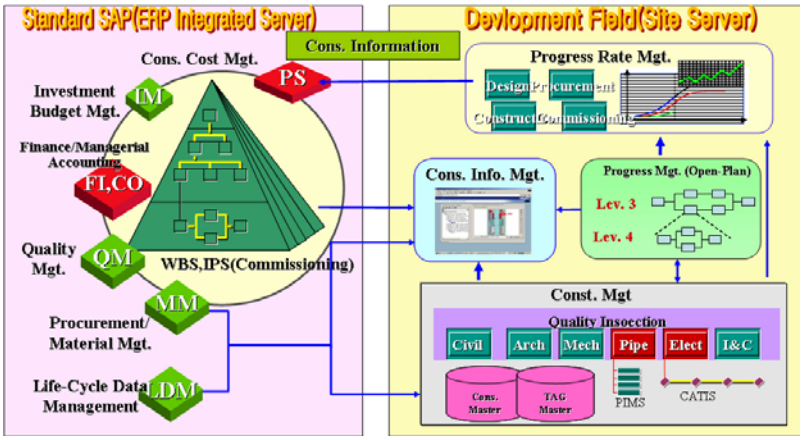

Figure 1. Construction Integrated System Implementation Plan

With the objective of simplifying the complex network of computing devices employed within NPP, modern technology and integration techniques are being used to form centralized databases and distributed processing and display networks.
Benefits are immediate as a result of the integration and the use of standards. The use of a unique data acquisition and database subsystem optimizes the high costs of engineering, as this task is done only once for the life span of the system. This also contributes towards a uniform user interface and allows for efficient expansion and maintenance. This paper features an information system as configured in Figure 1.

To establish a comprehensive project control program, controlling costs is very important method. Identifying the scope, quantifying the amount of work, and accurately monitoring progress are elements of a good method. Project control is not a set of stand-alone elements. NPP construction requires sophisticated project control systems to complete on schedule and within budget. Furthermore it needs integrated cost and scheduling systems and integration between each project entity for effective project control. Therefore, the development of this control system enabled NPP to fully use the network system that deals with designed drawings, engineering data, and supplier that supplies materials and machineries. To deliver huge information for business management, implementation of information delivery system should be preceded such as method for providing data, procedures, and network formation. (Refer to Figure 2)

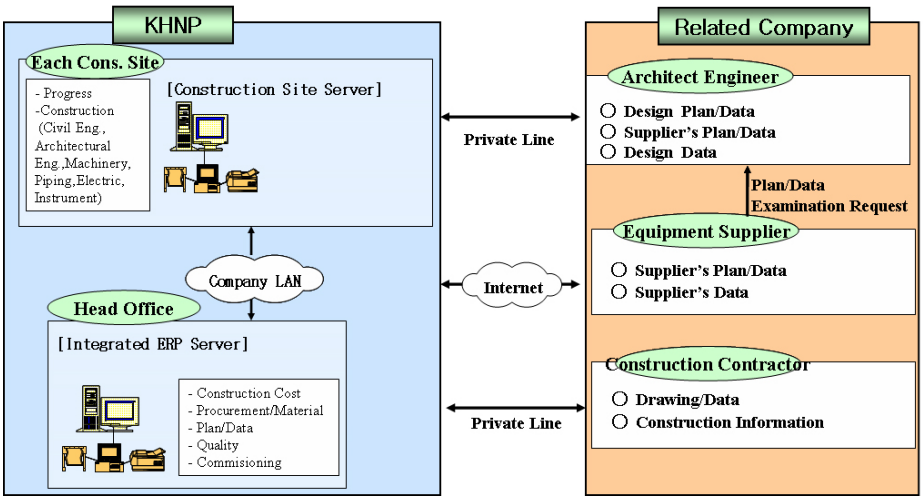

Figure 2. Network Structure

The network helps communication among A/E, contractor, and owner (stakeholder). Basically NPP manages a lot of data, drawings, bills, and specifications. Those design model information and image information are extracted with Engineering Database (EDB) and provided to owner. The network can quickly identify not only individual drawings and tagged equipment for each construction activity but also the status of each activity.

4. BENEFITS OF AN INTEGRATED INFORMATION TECHNOLOGY

The expected benefits of an integrated information system in a nuclear power plant construction are as follows;

- Make the most out of the existing signal wiring (network data), and have the capability to access every piece of information from every IT console (PC, PDA etc.).
- Improve both resolution and response time, with the evolution of hardware (workstations, persona computers, local area networks, etc)
- Improve communication through the construction information sharing and exchanging
- Integrated business process reduces duplicate work and it improve work productivities
- Accuracy and simple data can be used by standardization of recording form and procedures
- Historical data for re-used in further project

According to integrated information system for NPP, every management revision requires analysis, validation, and qualification of the process. This process takes into account the original design requirements.

After an analysis of the impact of the change in plant management, a team of engineers must compile all the documentation into a single document. Then detailing all the changes and its engineering documents are assembled. Therefore, those are

evaluated and approved by leaders who involved each area (civil, mechanical, and so on) easily. Basically those responsible for the affected documents are reflected the as-built state of plant.

Korea Hydro Nuclear Power (KHNP) has been analyzed about 700 forms from around 200 procedures and level of 'paperlessization' by using the integrated information and a network system. The fields were Civil & Architecture Engineering, Machineries, Electricity, Instrumentation, and Piping. The result shown in Table 3, each stage reduced 30.2% in the paperless. The concept of 'paperless' is not only to reduce the overhead cost but also to deliver information to the parts of each stage on a real time basis and to improve the efficiency of control management.

<Table 3> Electronic Approval System Result

Fields	Items to be Analyzed	Level of 'Paperlessization'		
		Electric Approval*	Images**	Work by hand
Civil Engineering	267	87	121	59
Machineries	302	29	258	15
Electricity	62	41	16	5
Measurement/communication	40	24	8	8
Pipelines	32	32	-	-
Total	703	213	403	87

*Electric Approval: As data that has items to be managed, its level of importance is high and needed to be shared with other fields
**Images: Low level of importance, not too valuable as data

NPP construction must break down to the lowest level work stages. It includes unique work number, installed volume, information on locations and references. Table 4 shows a sample of inspecting stages. Each stage report helps grasp the point of progress in upper level of scheduling.
This effort included developing or assisting in the development and maintenance of the project identification system, the material index and material tracking system, the construction activity packaging system, and other project documents.
The material tracking system monitors equipment from the initial engineering stage through procurement, warehousing, construction, and into startup testing.
The integrated project schedule is a primary management tool. This reference document identifies contract commitments between each entity. The document contains a detailed CPM schedule for engineering, construction and startup.

5. CASE STUDY

5.1 Uljin 5 and 6

Piping information technology system which was applied during construction of UlJin 5&6 was carried out with the goal of 'paperlessization of whole piping processes.

<Table 4> Inspecting Stages by Work Type

Fields	Types of Work	Inspection Stages	Achieved Level	Report
Construction	Steel Frame Work	Preparation		Inspection Report On Steel Frame
		Building steel frame	60%	
		Filling Grout in base plate		
		Measurement		
		Bonding of Bolt	90%	
		Bonding of Weld		
		Coating	100%	
	Coating	Checking of work condition		Inspection Report On Coating
		Checking of used materials	30%	
		Mix		
		Coating	90%	
		Drying coating	100%	
		Elimination of pollutes		
		Test of adhesive force		
	Installation of Measurement Instrument	Welding of strut (Manufacturing)		

The development of the system was completed in July, 1999 and the system was applied in the plant site in September, when piping construction began.
This construction of piping is a work of installing pipe such as welding pipe and designing pipe and in the system, the function that deals with process work such as inspection plan, notification, review of document, etc. and the function that prints any kind of reports for statistical analysis, using history data. 32 cases of construction procedures were reviewed, 22 cases were complemented and 32 kinds of inspection recording sheet were standardizes and approved electronically.
For information sharing, network system was formed with contractors at the job site so that any drawings and construction information can be used in real time.

5.2 Utilization of the System

September 1999, the pipeling construction began. End of March 2004, the performance of utilization of the system is quite satisfied. At that time it has been about 100% of construction completed, and also about 400,000 of work master has been implemented among the construction.
For the preceding projects, a construction supervisor from construction companies dealt with about 330,000 documents related to installation of pipe by hand, referring to design drawings and construction

data. A construction supervisor made reports of inspection plans or notifications as hard copy so that a supervisor had to go through 3-4 stages to get them approved. Also, notification and input of results from inspection are managed consistently by this system. Results from inspection are printed in the form of reports or kept in the Lifecycle Data Management (LDM) separately to manage them electronically.

5.3 Assessment of the System

Although the system was implemented and utilized for piping field among all the construction fields in constructing UlJin 5&6, the system focused in establishment of construction information management system, standardization of work processes, and collaboration of companies. Other related works have been affected by this system. There have been improved in many areas after using the system (Figure 3). 1) Drawings are delivered electronically and printed out at the plant site. It took more than a week to use hard copy drawings before. 2) Inspection plan and approval work took about 4-5 days but it is shortened to 1-2 days.

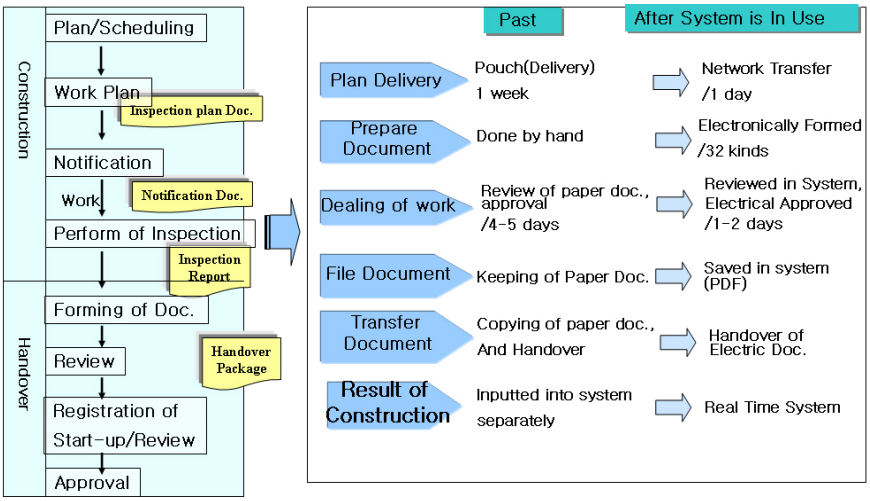

Figure 3. Assessment of System

3) All the drawing procedures are saved in the server as electronic files so that anyone related to construction can look for data in real-time, which shortened the time and papers spent on work processes. 4) It is possible to calculate the rate of construction process so that requiring work volumes and materials can be estimated by using history data. 5) In the line of assuring the quality, by managing the history of inspection with the name of the person who was in charge of the inspection such as worker, inspector and quality manager, the system helps to use electronic name system. 6) Information sharing system between owners and contractors improved the transparency of work. This case can be regarded as a successful example, which proved the possibility of rapid and accurate work management.

6. CONCULSION

Information technology in each designing, scheduling, cost, material, and data management has been segmental operating in the previous NPP projects. Uljin 5&6 implemented integration and interfacing information technology system for pursuing better control the project. In other words, project management using information technology affect the majority of the project cost. Using integrated information system in a NPP is gathering following conclusions;

- NPP construction should be managed thoroughly from the planning stage. Various construction-related organization as well as individual should now be able to utilize information system for better communication and collaboration.
- The concept of 'paperless' is not only to reduce the overhead cost but also to deliver information to the etities of the organization (internal & external) on a real time basis, or as close to real time as possible.
- The conventional practice of a three-week look ahead or 6-month-rolling schedule is no longer efficient. When something occurs that influences or affects the schedule, it should be updated to project schedule in real-time.

There can be proved a great result if this information system in NPP construction is applied to privatized construction business such as building apartments or public work of large scale like constructing high-speed railroads.

Acknowledgments

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Use Object Oriented, Visual Modeling, PDA to Construct Specification Inquiring, Quality Inspection and Site Recording System

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1. ABSTRACT

The construction market has been declined significantly for last few years in Taiwan. In order to survive in such difficulty environment, we have put some efforts on improving construction methods, creating new materials, and some other aspects. However, the most important factor to assure the success for construction companies is to perform construction management practically. We need to control each stage, from bidding, purchasing, and construction, very carefully so we can stay in good competition and maintain good profit.

In this research, we use Object Oriented, Visual Modeling, Rational Rose, and UML, combined with Delphi to construct the Construction Management Integrated System (CMIS). To link with PDA, user can inquire contract, specification, quality inspection tables and other related information.
This system can provide bi-directional data transformation, which allows user to down load data from PC to PDA and collect site information from PDA to CMIS in PC. The advantages of this system are as following: (1). to systematically make up the specifications and quality inspection tables, (2). to transform specifications, requirements, and other necessary information to PDA so engineers can read them immediately, and (3). to collect site information and integrated to main system. This can be used to perform cost control and decision-making.

Keywords：Object Oriented, Visual Modeling, Construction Management, PDA, Quality Inspection

2. REASON AND PURPOSE

During the process of automation in the construction industry, people often find themselves facing many difficulties. This was mainly because they tried to do a good job on automation of construction management; and spent lots of money and time to buy the so-called "Integrated Construction Management System", or look for a software company on development, yet the expected result was hard to achieve.

In this research we use the Object Oriented and Visual Modeling combined with the user with Object Oriented Analysis (OOA), Object Oriented Design (OOD) and Object Oriented Programming (OOP) to develop by the system; which can solve the defects of traditional software development such as incompatibility of software to users' needs, the system can hardly cope with change of needs, and the difficulty of software maintenance and expendability.

Due to the advancement in computer hardware and software, we now have the palm computer – PDA - with little volume and light weight. No more forms and sheets need to be filled in manually, since the site personnel may record data via PDA and transfer information needed for the site from previous entering action; so actual work situation can be checked immediately and reduces the time of travel and mistakes on documents.
The data collecting system includes various automatic and integrated electronic forms for receiving information entered into the palm computer – PDA. There are the following advantages on using a PDA: (1) after integration, only basic non-repeated data are needed; because (2) when PDA enters data such as "Specification Inquiring, Quality Control and Administration of Construction Records", the integration of data will be higher. Thus the quality of data integration and promptness will be enhanced remarkably.

From the above features, the service quality on internet business is now better than the traditional service industry, the turnover is no longer limited by the number of staff, and the productivity is even larger than what the service industry can compete with. Should the construction industry intend to improve its productivity and competitiveness, it shall not exclude this trend of industrial evolution.

In respect to the above-mentioned current situation, we have developed a system of "Specification Inquiring, Quality Inspection and Site Recording System", which may perform a vertical integration thoroughly on the management of the construction site; as well as integrating all relevant data within the project lifetime via the Internet, and save the calculation result of preliminary work in the system for later operation. In this way, a large amount of repetitive calculation and key-in work can be saved, as well as prevention human error during calculation process. By analyzing according to actual project requirement, this research

has completed four modules in the system, namely the Basic Database, Item Specification, Daily Site Report and Quality Control.

3. FUNCTIONAL REQUIREMENT

The structure of "Specification Inquiring, Quality Inspection and Site Recording System" was based on the mechanism of "Using Object Oriented and Visual Simulation to build Construction Management Information System I & II" (overall structure is shown on Fig. 1), and the main modules include:

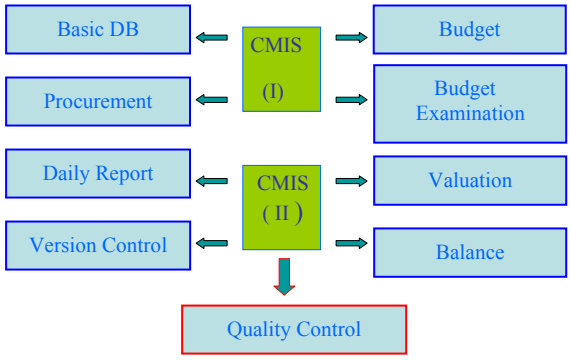

Fig.1 Structure between CMIS and this research

A. Build structure of basic information for the system, the database of work items are classified as large items, medium items, detail items, projects, buildings, floors, rooms, schedules and breakdowns etc.

B. Develop the Specification Module of that allows user to search for regulation on various work items, which act as important basis of site management.

C. Develop the Daily Site Report Modile that allows user to record number of people, machine, materials and work done on various items, which act as important reference for assessment and valuation.

D. Develop the Quality Inspection Module that allows user to enter data of quality inspection and print out its result, so effective quality management is achieved.

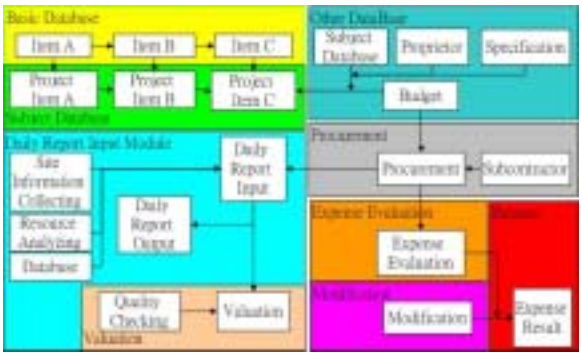

Fig.2 Relation between CMIS and this research

4. FLOW CHART OF RESEARCH

The flow chart of research for this program is shown in figure 3.

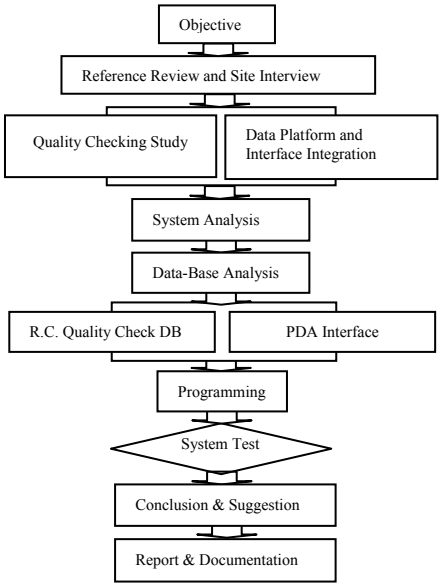

Fig.3 The flow-chart of this research

5. DISCUSSION ON DATABASE STRUCTURE

5.1 Analysis on database structure

The structure of the database is the main core of the system, once an error occurs in the frame, or users' requests are mismatched, the whole data flow will be in error, and put out unexpected information. Therefore, construction of a database frame that complies with functional requirements of the system is the key of success on a project.

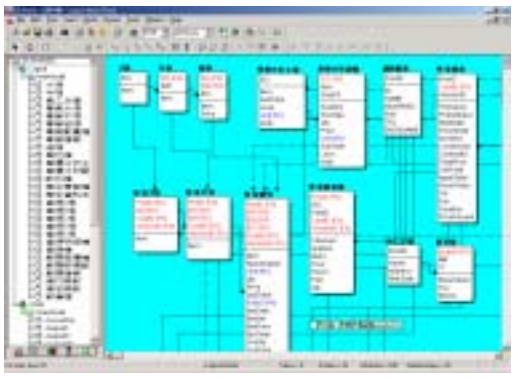

Fig.4 Relational model of the database

With the advancement of information technology, the development of database system has been performed from the traditional "Relational Database" to the "Object-Oriented Database" (OODB); and the OODB has become a major trend of managing system for database. This research uses the "ER /Studio (Entity-Relationship)" to produce an "ER Diagram", and then based on this model to plot the data flow chart in accordance with the user's requirement, so that an E-R Model is built. After defining the fields and relationship between fields on each data table, the actual database is then constructed, and becomes

the actual relationship database (as shown in figure 4).

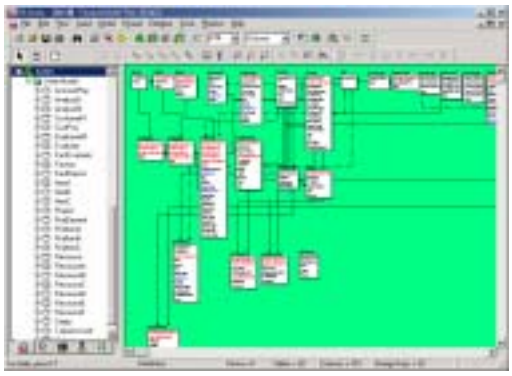

Fig.5 Physical model of the database

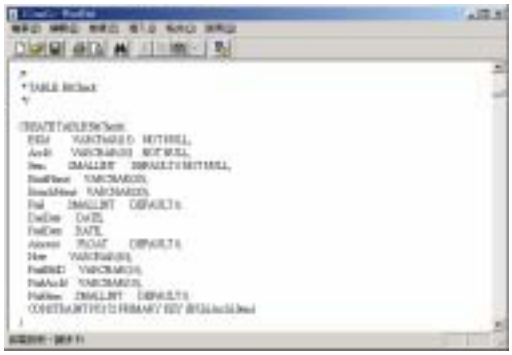

Fig.6 Script file of the database

After completion of ER/Model, we can use tools provided by the software to transform the database frame into a Script File (as show in figure 6) for database management system; which allows the Database Console to read database of the system, fields and properties of each data table, as well as connection of Primary Key and Foreign Key for each dat a table, so that the system database can be established. There are many transferable types of database, which are compatible with most of the major database management systems (as shown in figure 8).

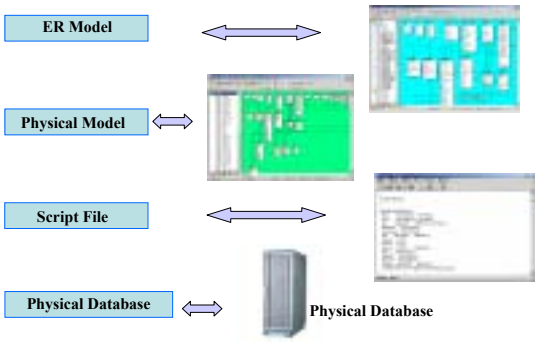

Fig.7 Flow chart using ER/Studio to generate Database

5.2 Specification Module

The construction Specification is the basis between the site contractor and sub-contractor on communication of what to do with certain work items. Therefore, if there is a regulation for reference at all times during site construction, it will provide great help.

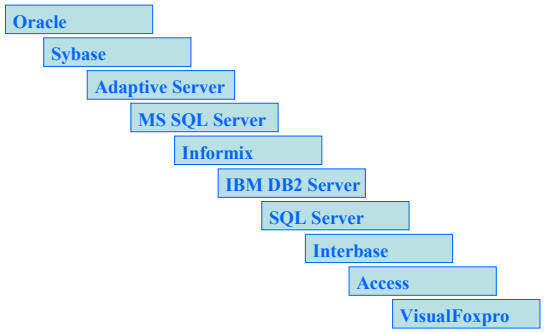

Fig. 8 DBMS that is compatible with ER/Studio

Based on the construction stages, the construction Specification is divided into the following categories:

A. Temporary work
B. Underground excavation
C. Structural work
D. Mortar work
E. Interior finish
F. Exterior finish
G. Doors and windows
H. Kitchen and toilet equipments
I. Electrical and mechanical work
J. Cleaning
K. Landscaping
L. Miscellaneous
M. Material

Figure 9 shows the screen of the searching system for formwork specification.

Fig.9 Specification Inquiring Dialog

5.3 Quality Inspection Module

During project execution, there are a tremendous amount of problems for the site manager to deal with from the start of work till completion of the project; this includes control of construction progress, arrangement of construction machines, cooperation of sub-contractors, arrangement of workers, entry of

material, arrangement of stored material, management of work quality, maintenance of site safety, handling of design change and mediation on dispute etc., where the range of professional information is extensively wide and complicated. Since the development of construction scale tends to be large and multi dimensional, the mission of how to systemize this type of problems further and how to manage the work well via computer/software systems will be the priority for site management of construction.

In the past, our construction management stayed at traditional hand recording or sending/receiving information with e-mail, and then establish relevant database by compiling manpower. This type of operation fashion would cause lack of integration between each unit and repetitive establishment of information. Furthermore, due to possible human error, possibilities of incorrect information, increasing cost, low efficiency, effect of work quality and future dispute would be created.

The current quality management in our construction industry is divided in three levels, which includes the owner and government authority, construction companies and professional contractors. For the inspection of quality control, most common procedures are filling in the inspection sheets of quality control and taking the sheets back to office for input of inspection result, where the construction personnel need to spend large amount of time and manpower on long and repetitive input of information. The construction industry has always been a industry with large amount of works, non-standardization and complicated breakdowns; thus the question of how to use the advanced hardware/software conditions from information technology and convenient wireless communication for site personnel on individual sites to input quality verification with PDA/Tablet PC, and use the wired/wireless communication to integrate such information with the main system immediately; where the contractor, construction companies, owner and government authority may access via internet and print out the result of quality verification, so that a computerized management of "24 hours/zero distance" can be achieved is a mission worth of effort by all.

Fig.10 Steel bar erection Input Dialog

Fig. 11 Steel Bar erection Print-out

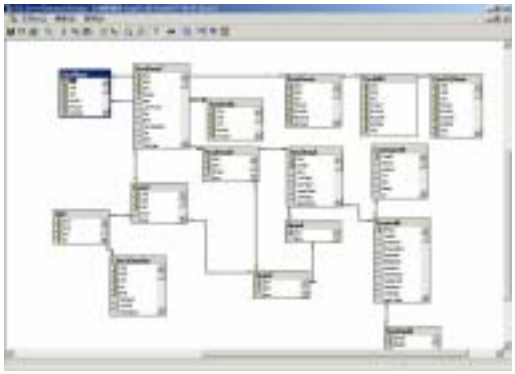

Fig. 12 PDA SQL Database Diagram

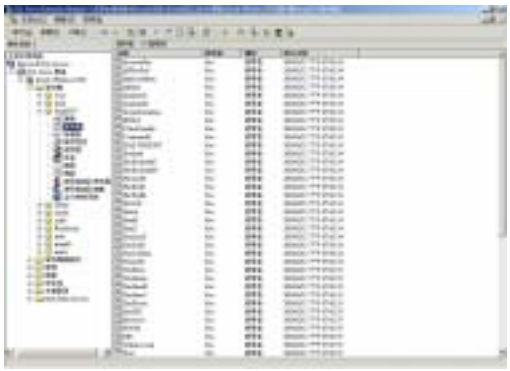

Fig.13 SQL Tables of PDA

Fig.14 Quality Inspection Dialog on PDA

5.4 Daily Site Report Module

The daily site work and various matter happen on site everyday, and it acts as the center of site management; where information collected from the site everyday may derive reports such as cost, progress and quality after sorting and analysis.

Since the daily work records and various matter happens on site everyday, and there are many things to be recorded, we therefore divide it into construction information, construction personnel, workers, machines, material, amount completed, work location, items of inspection, site memo and information of form completion.

The site records is not just filling in the daily sitereport, and it has to be used with other forms of records on weather, work duration, daily work hours, equipment usage, steel bar usage, amount of concrete pouring, amount of formwork and amount or earthwork; and the best is for the site records to cooperate with construction progress and network.

Fig.15 PDA Site Daily Report

Fig.16 Use SQL Analyzer to view Site Items

This system will extract the work items for database frame of daily site report from the basic database, and then transfer them as project work items, which is followed by compiling matters that happened on site and other relevant information (e.g. material analyzing database and information of contractors etc.) recorded in the daily work report system into information needed by the project items. The frame of buildings, floors and rooms will enter the work items per work location, and output the daily site report sheets via daily compiling; as well as the output of monthly report via monthly compiling in accordance with requirements of assessing period, and provide information to the assessment information system.

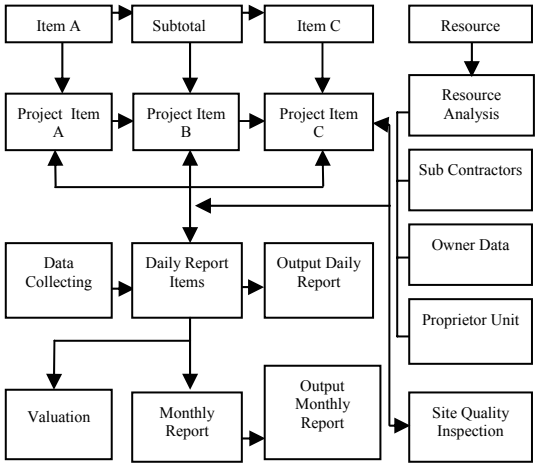

Fig.17 Daily Site Report and Quality Inspection Database

5.5 Building, Floor and Room Hierarchy

There is one common defect among compiling software in general building industry, namely the incapability of controlling amount of work done at every stage within limit. This research adds the frame of "Building → Floor → Room" into the basic database (as shown in figure 18), and compile with the database of project work items. If there is different rate due to different contractor on the work location included in the information of work items within the system, different part of this structure can be utilized to simulate actual execution, so the information of work items can be managed more adequately. Figure 19 shows the sample information as content of column and position of column on the information sheet for quality inspection of this system.

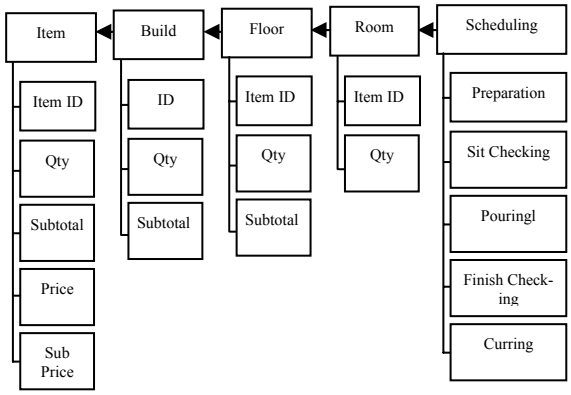

Fig.18 Build-Floor-Room Structure

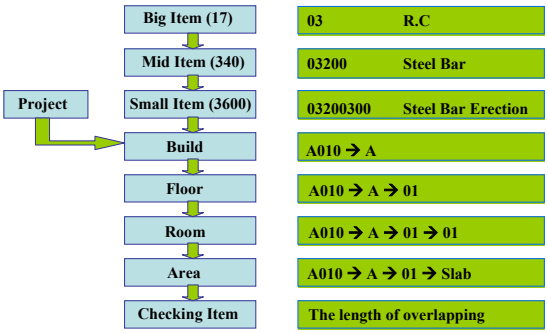

Fig.19 Quality Inspection Database Structure

6. CONCLUSIONS AND SUGGESTIONS

6.1 Conclusions

The handling via this research may contribute to the domestic construction industry as follows:

A. Collect and sort out existing systems of management in the construction market.

B. Help the overall construction industry to be familiar with the standard operation procedures and its content by using the system to unify operation procedures of construction industry.

C. From establishment of this database, unnecessary repetitive calculation on quantity and information entering can be prevented.

D. Utilize the systematic functions thoroughly, reduce traditional human errors, and carry out the managing systems and standard operations.

E. The systematic function may help decision maker to quickly find out the project content and make construction management well, so the decision maker can make better management with up-to-date information.

6.2 Suggestion

The consequent study of this research in the future is suggested as follows:

A. Combine with the progress managing software (e.g. MS Project, P3 etc.) for automatic compiling of work progress, and renew the information from daily work report into the progress managing software, so a up-to-date and complete construction management can be expected.

B. Compile all information on site for development of financial cost system, which can manage and control the work income and expense, as well as increasing profit for construction contractors.

C. Consideration of input the Daily Site Report into 3D animation and show work completed and construction progress.

Acknowledges

I would like to take this opportunity to show my appreciation to National Science Council, Executive Yuan, for its support of the study. Project No.: NSC 91-2622-E-216-007-CC3.

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Developing Analysis Models for Implementing Construction Enterprise Resource Planning System

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Abstract: To face the worldwide competition and pervasively use of new information technologies, enterprise resource planning (ERP) systems are executed and implemented to enhance their competition capabilities. In order to implementing ERP systems successfully in construction industries, an appropriate analysis model ICE-PP (IDEF0 in Construction Engineering with The Proven Path) is presented in the paper and executed in the real case for the implement of construction ERP system. The ICE-PP including sixteen processes used as a reference model for the construction enterprise to implement the ERP system. The paper mainly describes the real case that experience in Taiwan construction enterprise and explain the critical steps are needed for the important procedures to successfully implement the ERP system. Also, with the reference model, the implementing process could be improved effectively and reduce the probability of failing implementing ERP system.

Keywords: Enterprise Resource Planning; Construction Industry; Analysis Models

1. Intriduction

There are only a few construction factory cases that induct ERP. Besides, only the enterprises involved in the induct process know the key point. That is the reason why we lack of the important reference cases about construction factory induct ERP. Therefore, if we could establish the analysis model about construction factory induct ERP through literature review, experts interview and participate in one of them, the extra induct cost and chances of failure induction will reduce. In order to implementing ERP systems successfully in construction industries, an appropriate analysis model ICE-PP (IDEF0 in Construction Engineering with The Proven Path) is presented in the paper and executed in the real case for the implement of construction ERP system.[2][4]

2. The limit and Methodology of the Research

2.1 The limit of the Research

（1） Due to there are few factories implemented the ERP system in the construction industry, it is impossible to collect amounts of research samples such as that in the manufacturing, electronics and information industry. Therefore, the research only focuses on few representative firms.[2][3]

（2） Construction firms successfully implemented the ERP system had not exceeded one year, and still been pending in system adapting and transition stage. For the difficulty of analyzing their history information, financing and accounting forms, the research only can apply expert interviewing method to explore all kinds of problems and solutions involved in the implementing process.

（3） Although construction factories are core characters in the construction industry, the industrial behavior still includes architecture investment and contract work system. The scope of the research can be more extensive if studying in different characters within the construction life cycle. Though, for the restriction of the research, it focuses on proprietors, construction factories and professional contractors without the consulting firms and the architect offices.

（4） For the construction firm “company A” successfully implemented the ERP system, the research only can apply expert interviewing method and literature reviewing to comprehend the implementing condition.

（5） The construction firm “company B” had not entirely implemented the ERP system yet, the research only focuses on stages of plan to implement and partially implement progress for both companies, and applies literature reviewing, expert interviewing and practically participating.

2.2 The Function Analysis of IDEF0

This publication announces the adoption of the Integration Definition Function Modeling (IDEF0) as a Federal Information Processing Standard (FIPS). This standard is based on the Air Force Wright Aeronautical Laboratories Integrated Computer-Aided Manufacturing (ICAM) Architecture, Part II, Volume IV - Function Modeling Manual (IDEF0),June 1981.

This standard describes the IDEF0 modeling language (semantics and syntax), and associated rules and techniques, for developing structured graphical representations of a system or enterprise. Use of this standard permits the construction of models comprising system functions (activities, actions, processes, operations), functional relationships, and data (information or objects) that support systems integration.

This standard is the reference authority for use by system or enterprise modelers required to utilize the IDEF0 modeling technique, by implementors in developing tools for implementing this technique, and by other computer professionals in understanding the precise syntactic and semantic rules of the standard [5].

2.3 The Proven Path Implement Processes Method

The Proven Path brought out by Oliver Wight Company in 1990, focused on 16 implementing processes and detailedly analyzed steps and points for attention in every processes of implement MRPII, was regarded as an important reference of MRPII.[1]

（1） Audit/Assessment I：An analysis of the company's current situation, problems, opprtunities, strategies, etc. This analysis will serve as the basis for putting together a short-term action plan to bridge the time period until the detailed project schedule is develop.

（2） First-Cut Education： A group of executives and operating managers from with the company must learn, in general terms, how MRPII works; what it consists of; how it operates; and what is required to implement and use it properly.

（3） Vision Statement： A written document defining the desired operational environment to be achieved with the implementation of MRPII.

（4） Cost/Benefit： A process to generate a written document that spells out the costs of implementation and the benefits of operation MRPII successfully, and result in a formal decision whether or not to process with MRPII.

（5） Project Organization： Creation of an Executive Steering Committee; an operational-level project team, consisting mainly of the managers of operating departments throughout the company; and the selection of the full-time project leader and other people who will work full time on the project.

（6） Performance Goals： Agreement as to whtch performance categories are expected to improve and what specific levels they are expected to reach.

（7） Initial Education： Ideally 100 Percent, a minimum of 80 percent, of all of the people in the company need to receive some education on MRPII as part of the implementation process. People need to know what, why, and how these changes will affect them.

（8） Sales, Logistics, and Manufacturing Processes： A detailed statement of how the sales/marketing, logistics and manufacturing functions will operate following the implementation of MRPII, backed up by a detailed project plan necessary to achieve this.

（9） Planning and control Processes： Development and implementation of policies and processes necessary for effective planning and execution, from sales & operations planning down through the detailed schedules for the plants and suppliers.

（10） Data management： MRPII, to be successful, requires levels of data integrity far higher than most companies have ever achieved. Inventory recoeds, bills of material, routings, and other data need to become highly accurate, complete and properly structured.

（11） Process Improvement： Improvement in physical processes are the heart of a Just-in-Time implementation, and can play a significant role in Quick-Slice MRP. It's optional in an MRPII company-wide implementation, ofter not a major step. However, opportunities for improving physical processes should not be overlook-before, during, and after-MRPII implementation.

（12） Software： Acauisition, installation, and maintenance of the necessary softweare to sipport all MRPII functions.

（13） Pilot and Cutover：Beginning to operate the business with the new set of tools-on a very contrilled and closely managemd basis.

（14） Performance Measurements： Beginning to track actual results and compare them to the performance goals defined in step6.

（15） Audit/Assessment II： A focused evaluation of the company's situation, problems,

opportunities, and strategies following the implementation. It is the driver via which the company moves into its next improvement initiative.

（16） Ongoing Education：Initial education for new people coming into the company and refresher education for continuing employees.

2.4 The Amendment of The Proven Path

Though assume the principle of The Proven Path endures from MRPII to ERP, the application of the system software has been developed from manufacture resource to integrating all resource demand of the business. For this factor, it requires proper amendments. The main amendments are as followed: The (8) stage is “Sale, Logistics and Manufacture Processes”. For the enterprise resource planning includes five managements scopes such as manufacture, marketing, human resource, research, and finance, thus revises “Sale, Logistics and Manufacture Processes” to “Business Operation Processes”.

2.5 The coding method of the ICE-PP （IDEF0 in Construction Engineering of the Proven Path）

The coding method follows the coding principle of the IDEF0: first layer is A0 “Construction Firm ERP Project”, second layer are A1 “ERP Pre-implement Preparation” and A2 “ERP Implement Operations”, third layer are A11 “Audit/Assessment I”, A12 “First-Cut Education”, A13 “Vision Statement”, A14 “Cost/Benefit”, A15 “Project Organization”, and A16 “Performance Goals”, as shown in Figure 1.

3. Cases Study

The first case A, general contractor, established since 1984, contracts for general construction and build includes residences, hillside villas, office buildings, technology factories, school, hospital, and bundled or packed goods mart, etc. This firm adopts SAP System.

The case B was established since 1976. This enterprise had traditional Chinese operate characteristic, with American and Japan business culture and modern management philosophy. This enterprise was choiced People Soft System.

4. Comprehensive Discussions and the Analysis Model Revision

4.1 Discussions of Audit/Assessment

The main idea of classifying A11 “Audit/Assessment I”, A221 “Performance Measurements” and A222 “Audit/Assessment II” in to the “Discussions of Audit/Assessment” is to evaluate the present operation performances and future needs. Take A11 “Audit/Assessment I” for instance, the purpose is to determine the business present condition and bring out requirements of improvement and suggestion schemes. A221 “Performance Measurements” is to calculate the beneficial result of implement, and bring out the future possible improvement schemes in A222 “Audit/Assessment II”.

The stage of Audit/Assessment is the starting point of the project implement. If the company’s core objective is not defined certainly in this stage, it will lead to the result as “A small discrepancy leads to a great error.” Thus the Audit/Assessment is the key point of the implement.

According to the interviews, company B concerned to integrate construction management resource into the ERP system, while company A acquired to accomplish business operation and management. The reason that company A differs from other cases is which has already developed the construction management related application system before implementing ERP, and the system accomplished the construction management industry demand. As to the ERP system, accomplished enterprise resource planning of all subsidiary companies of company A. For different considerations, it results in different consequences in planning relative modules of the system. The research studies on cases and concludes several audit/assessment analysis scopes as follows:

The first is the demand scope, divided as internal and external demands. Internal demands include high-level supervisors’ and every divisions’ demands toward the system. For the work and finance division are the core in the construction industry, both divisions and high-level supervisors’ demands are supports for ERP project. External demands derive from all characters upstream to downstream in the industry, such as proprietors, construction factories and professional contractors, the enterprise tries to accomplish every different external demands to catalyze ERP project.

The second is the integration scope, includes cross processes, cross divisions, cross projects and cross undertakings integration. The cross processes integrations, implies as small as the construction sites coordination to as large as the material factories and manufacture factories coordination. The cross divisions integration, coordinates the construction project division and financial accounting division, as the most complicated example in the construction industry. The cross projects integration implies the resource modulation and distribution within projects. The cross undertakings integration implies plan, design and materials supply coordination, or

construction and mechanical and electrical assembling projects coordination.

The third is time scope, approximately sorts out as short-term, medium term and long-term stages. The short-term stage includes business demand and resource modulation. The medium term stage implies integrating all internal resource in business, and improving the business competency. The long-term stage plans for supply chain integration, cross regional organizations coordinative design integrations, and etc.

From another point of view, the integration scope implies the character of demander, but as if to integrate the processes in construction sites, implies the executors' demand. As to integrate the resource within divisions and projects or even cross undertakings, it implies demand of operation and management or strategy development scope.

4.2 Discussions of Education/Training

The research concludes A12 "Initial Education", A211 "First time Education" and A223 "Continued Education" to the "discussions of education/training", and the relative topics are as follows:

Before the selection, or after the selection but before implement the ERP system, it is necessary to train the ERP group for concepts, rear-end management of the system and implement methodology, to make the group members acquaint to the ERP system as large as an aircraft carrier, and make them more familiar with the system implement to implement the ERP project favorably.

Refers to company A with SAP system, and the two bid soliciting teams, the main principle of the education/training is to train seed members by consultants, then designed the user's guidebook and trained general users by seed members.

The research discovers that case companies both have common characteristic, which is to train internal employees constantly to keep enterprise progressing and maintain as a market forerunner. Wherein the enterprise with larger training budgets authorizes management consulting company to train, and that with fewer budgets attends the educations hold by the government or academic circle.

From case study and expert interview concludes that the education/training in the implement progress is the key factor for practically execution in the future. If it is possible to train general users as seed members, the system is able to bring the largest beneficial result. However, the biggest problems are the system acquaintance of general users and the concept recognition of operation processes among divisions. Thus by constant training, conquers the obstacles of practically implementing the system.

4.3 Discussions of Visions and Goals

The research concludes A13 "Vision Statement" and A16 "Performance Goals" to the "Discussions of Visions and Goals". Visions are abstract description, while performance goals topics are more specific, but both are objectives traced by every divisions and stratums no matter neither abstract nor specific.

The enterprise visions in the studied cases, company B planed to integrate the resource among construction related undertakings in short-term, and to integrate the whole resource within the company group in long-term. Company C planed to eliminate the old system and improve enterprise competency in short-term, and to expand domestic and foreign engineering construction markets in long-term. Every factor of vision statements and performance goals derives from internal audit/assessment. If it is possible to point out the enterprise demands, and plan for short-term, medium term and long-term strategies, visions and goals induced by demands will be obvious, and will provide bid tending factories more certain develop policy to bring out solutions much specifically.

4.4 Discussions of Cost/Benefit Analysis

Cost constitutes of the human resource cost, the administration cost, the consulting service cost, the training cost, the system cost and etc. The human resource cost includes planning team and implementing team. The administration cost implies all conferences cost within the progress. The consulting service and training cost divides in internal and external parts. The system cost contains expense of software and hardware.

According to the analysis of consultant service data of company A in the research, the manpower time require for the project module is higher than any other application module. Obviously, the importance of the project management in the construction industry is not substitutable for other modules.

4.5 Discussions of Project Organization

According to the project organization of the studied cases, the larger scale of the enterprise, the higher cost of human resource. In every division, even the human resource distribution of the ERP system module, at least one seed member of specific duty is required. Seed members simply with information background are also appreciated. On account of members with information background not only can make effort to information techniques within implement progress, but also perform assistant roles for the unacquaintance to information techniques, and which can improve team cooperation and beneficial results of implementing. Moreover, as the maintenance point of view, information members

should transfer the techniques from consultant service into enterprise internal, thus can handle on its own when requiring for maintenance in the future, and can code reporting program on its own when requiring for list reporting, without help by hiring consultants.

4.6 Discussions of Planning and Control Management

The main idea of planning and control processes is the project management of the implement process. The research based on cases study concludes several management points such as schedule management, cost management, document management, communication management, contract management, risk management and etc. Wherein the cost management is mentioned above in the Discussions of Cost/Benefit Analysis, so this section describes progress, document, communication and contract management.

The principle of schedule management: After permission of high-level supervisors, project members establish the implement time arrangement together with consultants. Every activity should follow the time arrangement. If encountering sudden events or progress delay, it must response to the high-level committee to make proper revision toward the plan schedule.

The principle of document management: In the entire progress from the first implement conference to fully implement, every relative documents should be categorized systematically, such as conference records, conference briefings, references, implement documents, training materials, and etc. It will be much easier to acquire and absorb information in documents in the future if which can be categorized more systematically. Besides, documents should backup periodically and even in other place, to prevent from irresistible accidents and reduce the risk of implement failure.

The principle of communication management: the communication management is for internal and external. The internal objects are company project members, and the external object is the implement consulting company. The internal communication requires high-level supervisors endow sufficient right, responsibility and obligation to diminish the coordination and integration of internal organization, and avoid unnecessary disputes. The external communication requires curtailing the acquaintance divergence between the implementing company and the implement consult, and maintains intimate communication. If it is lack of freely communication between the both, the acquaintance divergence of project demands will increase the risk of implement failure.

The principle of contract management: The contract management of implement ERP system is the key point of protecting both sides rights and obligations. In addition to the check and accept payment mechanism, the maintenance of operation of ERP system is the main part in the contract.

4.7Discussion of Information Technology Topic

The topic of information technology was combined A214 “Data Manage” and A216 “Soft”. This topic not only includes each enterprise’s original imformation system such as schedule management system, drawing and design system, document management system, engineering management system, bus also includes the modules of ERP system, for instance materiel management, pocurement management, cost control, contract management, funding management, knowledge managemtn, quality management, facility and maintenance management, asset management, finance and ccounting management, sales management , production management, EIP, marketing analysis system , bidding preparation management, and human resource management ect.

To collect the orginal system for general contractor, it would be easily understand the main system was focus on construction engineering management (planning and design, cost estimation, and scheduling).

The research listed all of modules from this case study, and classified the characteristic of construction management, business management, and cross industry. The Table2 was statistics five modules of construction management, six modules of cross industry, and ten modules of business management.

5. Conclusion

The characteristic of this research is the systematic analysis model that established by logical way. The study based on the real cases of Taiwan implements ERP. Future study could modify the model in different angle, such as owner, architect, consultant etc., this will strengthen this model’s generality and substantially reduce and properly control the uncertain factors when construction factories induct ERP.

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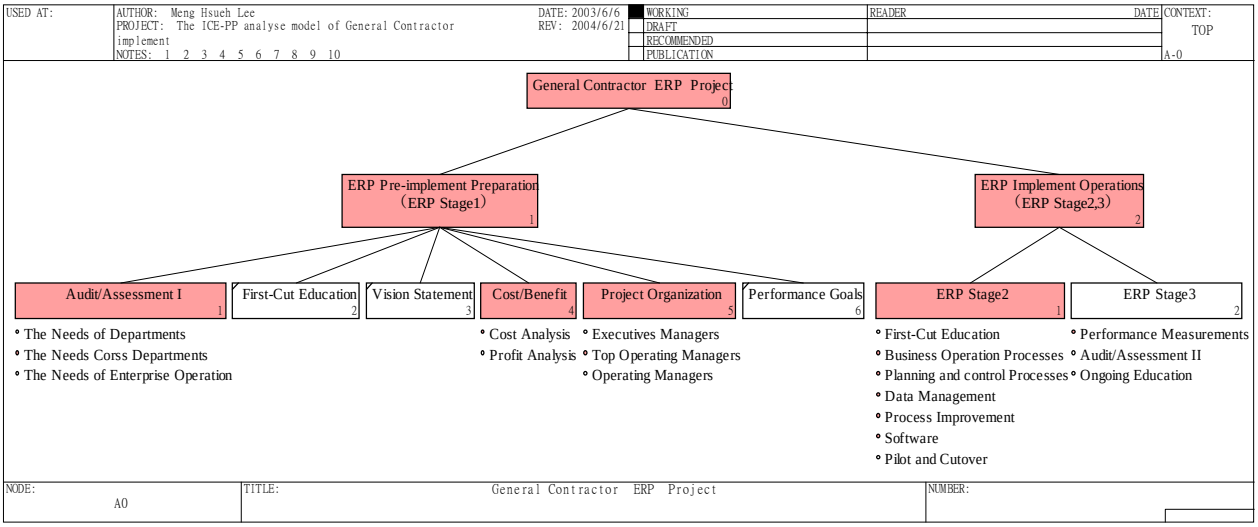

Figure 1. The Diagram of ICE-PP analysis model

Table 2. Comparing ERP modules from case studies

ERP System Module Name		A	B	Industry Category
1	Materiel Management	O		Cross Industry
2	Pocurement Management		O	Cross Industry
3	Cost Control	O	O	Business Management
4	Engineering Management			Construction Management
5	Contract Management			Construction Management
6	Engineering Planing and Schedule Management	O	O	Construction Management
7	Fund Management	O	O	Business Management
8	Knowledge Managemtn		O	Business Management
9	Quality Management	O		Cross Industry
10	Facility and Maintenance Management	O		Cross Industry
11	Asset Management	O	O	Business Management
12	Finance and Accounting Management	O	O	Business Management
13	Sales Management	O		Cross Industry
14	Document Management System	O	O	Business Management
15	Production Management	O		Cross Industry
16	EIP		O	Business Management
17	Marketing Analysis System		O	Construction Management
18	Bidding Preparation Management		O	Construction Management
19	Capital Management		O	Business Management
20	Account Management	O	O	Business Management
21	Human Resource Management		O	Business Management

DEVELOPMENT OF AN XML SCHEMA REPOSITORY SYSTEM FOR PUBLIC CONSTRUCTION INFORMATION SHARING

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Abstract: The Public Construction Commissioner (PCC) in Taiwan is sponsoring a project to establish the mechanism for developing information standards, in terms of XML schemas, for public construction work and develop an XML Schema repository system for managing and publishing the standardized XML schemas. Parts of the ebXML (Electronic Business using eXtensible Markup Language) Registry Information Model (ebRIM), Version 2.5, proposed by OASIS (Organization for the Advancement of Structured Information Standards), are adopted in the design of the repository system. This paper reports the progress on the development of the repository system in the project.

Keywords: XML schema, Repository, Information standardization and sharing, ebXML, Public construction

1. INTRODUCTION

In recent years, Taiwan government has made many efforts in providing government e-services, including government-to-government (G2G), government-to-business (G2B), and government-to-customer (G2C) services to its client users via Internet. For example, in the area of public construction, the government procurement information is now available through the Internet and on-line tendering services will be provided soon. Furthermore, a project has recently been sponsored by the Public Construction Commissioner (PCC) to promote exchange and sharing of life-cycle construction information in Taiwan. There are two major tasks to be accomplished in the PCC project. The first one is to establish the mechanism for developing information standards, in terms of XML Schemas, for public construction work. The second task is to design and implement an XML schema repository system for managing the standardized XML schemas and providing schema search and retrieval services on World Wide Web (WWW). This paper reports the progress on the development the XML Schema repository system in the project.

In the rest of this paper, requirement analysis of the repository system is discussed first in Section 2. Then, the design of the system is presented in Section 3. The Unified Modeling Language (UML) [1-2] is employed in this work for object-oriented analysis and design of the repository system. Section 4 discusses the implementation of the system and provides some demonstrations on the web interfaces and services of the system. Finally, some conclusions are drawn.

2. SYSTEM REQUIREMENT ANALYSIS

The main purpose of the repository system is to store, manage, and publish the standard XML schemas and their corresponding documentation for information sharing and exchange in public construction work. The repository system also stores and manages a data dictionary containing definitions and synonyms of all of the vocabularies used to define the tag names in the standard XML schemas. Each of the tag names is unique and named in English. Its corresponding Chinese tag name and related attributes are also defined in the data dictionary. Furthermore, an XML schema for the data dictionary is developed and standardized in this work.

For development of standard XML schemas and the corresponding data dictionary, a standards establishment committee has been organized by PCC and a standards establishment mechanism has been established. Once the new version of a standard XML schema is approved by the committee, it is registered into the repository system for publication on WWW. The contents (mainly the tag names and their attributes) of a newly registered schema are validated by the system to ensure that they have been uniquely defined in the data dictionary. The system should also provide query and download services for its client users to search and retrieve the standard XML schemas and related information in the data dictionary needed for their work. Furthermore, the

client users may need validation services for checking the validity of their XML documents to a specific standard XML schema. In addition, system administration service is needed for maintenance and monitoring of the system.

Based on the above requirement analysis, the following major services should be supported by the repository system:

- System administration service: This service provides the necessary functions for managing user accounts, maintaining schema data and data dictionary, monitoring system performance, etc.
- Registry service: This service provides the necessary functions for the standards establishment committee to register and publish the approved versions of standard XML schemas as well as the updated data dictionary.
- Query management service: This service provides the necessary functions for searching and retrieving a specific standard XML schema and its associated information in the data dictionary.
- Content validation service: This service provides the necessary functions for validating the new or updated XML schema when it is registered into the system and for checking the validity of a given XML document to its corresponding standard XML schema.

Figure 1 shows the major services and applications of the XML schema repository system. All of the services, except of the system administration service, are mainly provided in the form of Web Services [3-4]. A public construction information portal, which is currently being constructed, will provide web pages for the users to have easy access to the query management and content validation services of the XML schema repository system.

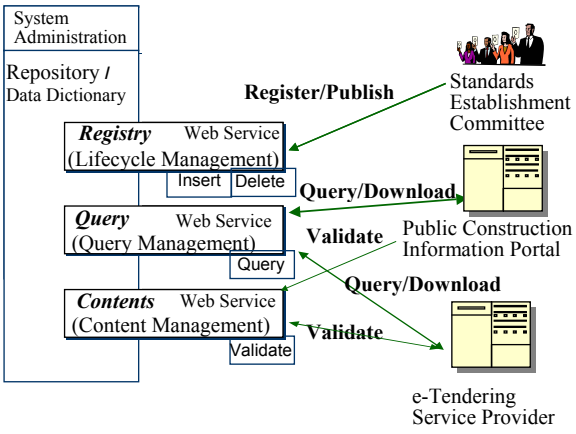

Figure 1. Major services and applications of the XML schema repository system

3. SYSTEM DESIGN

Parts of ebXML (Electronic Business using eXtensible Markup Language) Registry Services Specification (ebRS), version 2.5 [5], and ebXML Registry Information Model (ebRIM), version 2.5 [6], proposed by OASIS (Organization for the Advancement of Structured Information Standards), are adopted in the design of the repository system. For designing the services of the system, the following parts in ebRS v.2.5 [5] are adopted in this work:

- Lifecycle management service: It provides a collection of lifecycle management methods for managing objects within the ebXML registry. The client user may submit objects, classify and associate objects, and deprecate and remove objects.
- Query management service: It allows a client user to discover and retrieve information from the ebXML registry. The client user may browse through and issue queries on registry contents.
- Content management service: It uses the content validation service to enforce validation rules upon submitted contents and metadata in a content specific manner.

For designing the classes in the information model of the XML schema repository system, parts of the ebRIM v2.5 [6] are adopted in this work. Figure 2 shows the high level public view of the ebRIM information model. Although the version (i.e., v2.5) adopted here is just a committee approved specification and is not a final release version (which will be v.3.0), it seems to be very close to the upcoming final release version. In this work, only the following classes in the ebRIM v2.5 information model are adopted: the RegisterEntry class, ExtrinsicObject class, User class, Organization class, PostalAddress class, TelephoneNumber class, Association class, ClassficationNode class and Classification class.

Figure 3 shows the class diagram for the object-oriented design of the data dictionary. The corresponding XML schema design for the data dictionary has been approved by the standards establishment committee.

Because the relational database is still the most popular and widely used database, it is employed in this work to store and manage the information objects associated with the XML schemas and the data dictionary. The entity-relation (E-R) model diagrams for the schema repository database and the data dictionary database are designed as shown in Figs. 4 and 5.

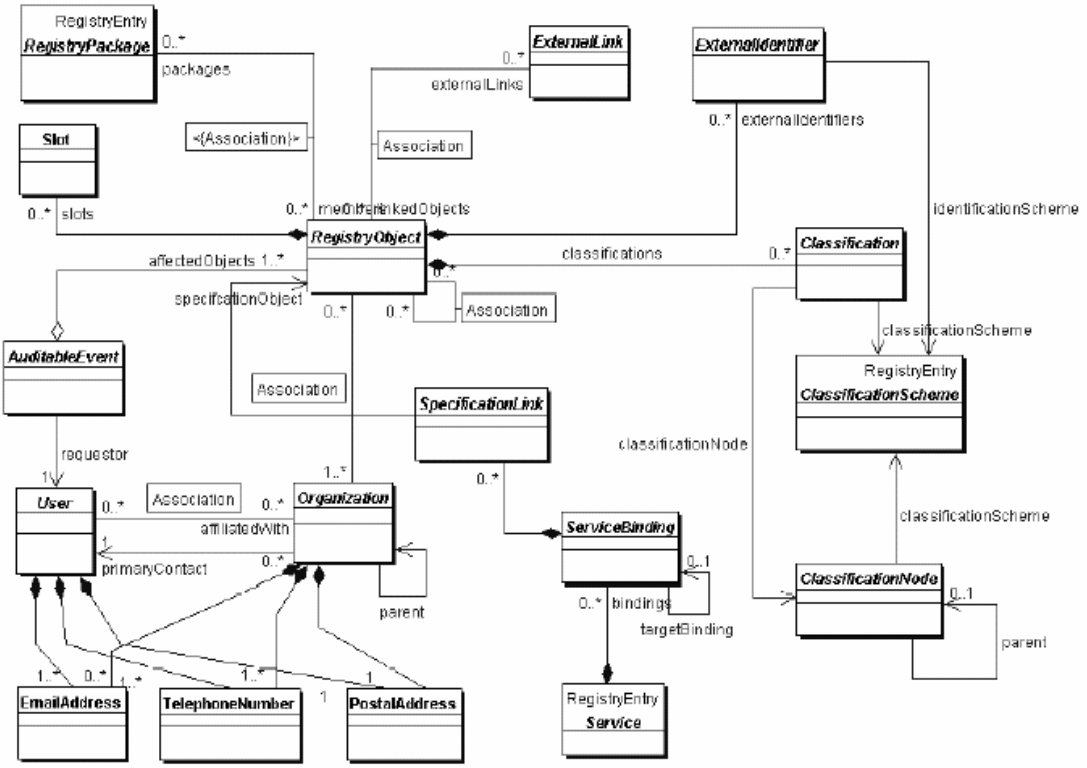

Figure 2. The high level public view of the ebRIM Information model [6]

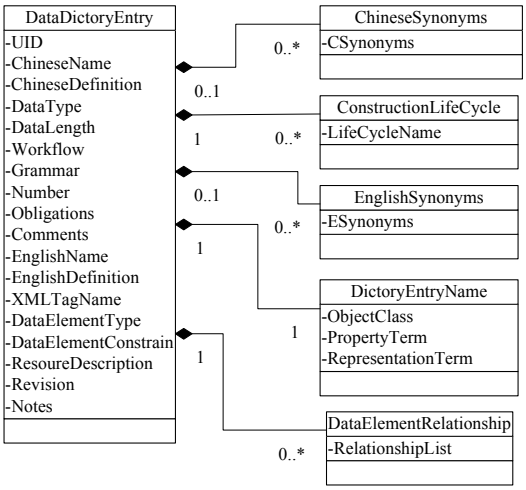

Figure 3. Class diagram for the data dictionary

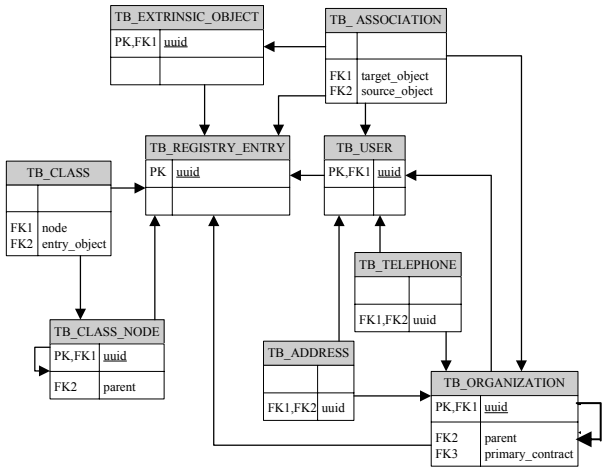

Figure 4. E-R model for the repository database

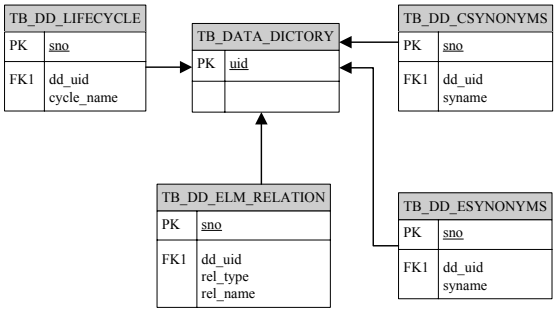

Figure 5. E-R model for the data dictionary database

4. SYSTEM IMPLEMENTATION AND DEMONSTRATION

The implementation of the XML schema repository system requires two servers: database server and web server. This work employs Informix v9.4 as the database server and Resin v2.1.10+SLL as the web server. The operating system used for running both servers is the RedHat v8.0 Linux. The programming language used is the Java programming language. In addition, the Java WebService Module (Axis v1.1), the Java Upload Module, and FullText-Search for Informix are used to facilitate the implementation of web services, uploading service, and searching service for the repository system.

Most of the basic service functions for the repository system have already been implemented although more work is still needed to complete the system implementation as designed in Section 3. Figure 6 shows the home page of the repository system. At present, all of the system interfaces are in Chinese. The web page shown in Fig. 7 illustrates the results of a conditional query on the standard XML schemas in the repository. Figure 8 demonstrates the query result, expressed in tree format, on a specific XML schema. The query result can also be expressed in the table format. Figure 10 shows the query result of the data dictionary information.

Figure 6. The home page of the repository system

5. CONCLUSIONS

The progress of an on-going project on development of an XML schema repository system has been reported in this paper. The system is designed to promote and facilitate information sharing and exchange for public construction work in Taiwan. The standard XML schemas and the data dictionary managed by the system are two essential components to achieve the goal. They are also important assets of the construction industry because they represent the results of accumulated knowledge and experiences in the public construction work. It is hoped that the repository system can provide good services for maintaining and querying standard XML schemas and help to promote the use of information standards in Taiwan's construction industry.

ACKNOWLEDGEMENTS

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Figure 7. Results of a conditional query

Figure 8. Query result (in tree format) on a specific XML schema

Figure 9. Data dictionary information query

AN OBJECT-ORIENTED DATABASE FOR PROJECT COST COMPILATION

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ABSTRACT
Larger construction companies generally have several on-going projects at one time, many internationally. The ability to make corporate decisions in a timely manner for these companies becomes critical to avoid costly corrective measures. The information necessary for making such decisions comes from a large pool of corporate data. In order to efficiently process large amount of data, an information model for multiple project management is essential.
In this research, an information model based on *Cost* is designed and presented (OCIM, Object-oriented Cost Information Model). A prototype system is developed based on the model using an object-oriented database. Using the periodical update feature of the prototype system, an immediate access to necessary information by the user is made possible. The different levels of information abstraction are also achieved to meet the different level of the user.

KEYWORDS: Construction, Cost, IT, Database, Object-oriented, Information, Multiple Project Management

1 INTRODUCTION

A construction company has to carry out and manage several projects at a time. Larger firms deal with hundreds of projects spread nationwide and often worldwide. As the number of projects within a firm increases, it becomes difficult for top management to keep track of progress, and thus, to control the projects. The difficulties come from the complexity of collecting, processing, and utilizing information for managing multiple projects.
The construction industry benefits from the advancement in modern information technology (IT) in computerizing many practices otherwise performed manually. Many software applications have been actively adapted for construction management; however, most of them only support a single project. A system that can integrate multiple project management information has become necessary for many construction firms where corporate decision makings over several projects are critical.
In order to provide information necessary for making corporate decisions, a well integrated information system is essential. The system must be able to deal with the complexity of the construction information as well as the large number of individual organizations participating in the projects. Further, the information should be available whenever and wherever because failure to make timely decisions means potential financial losses. In this research *cost* is used as a parametric measure of progress and other project performances [2]. Various forms of project costs are modeled for the database development. This research proposes *Mapping Objects* which periodically process project data into multi-project information. A *Mapping Object* is a neutral connector between separate modules that collects compiled data from corporate database.
An object-oriented database is used to properly demonstrate the proposed information model [3]. A cost information model for the database is designed with maximum efficiency in large data compilation as its primary objective.

2 COST INFORMATION MODEL

Cost is used as an important element of the information model in this research. *Model* refers to the complete view of all the elements in an information system. An information model of construction cost is developed for the database system.

2.1 Cost Information

Generally speaking, *cost* is a monetary value of an item. It is used as an indicator of business

performance. Daily progress, project performances, and regional business status can be all represented in dollar amounts [2]. This research organizes cost information along the three axes of (1) Cost Type, (2) Cost Lifecycle, and (3) Change Order as illustrated in Figure 1.

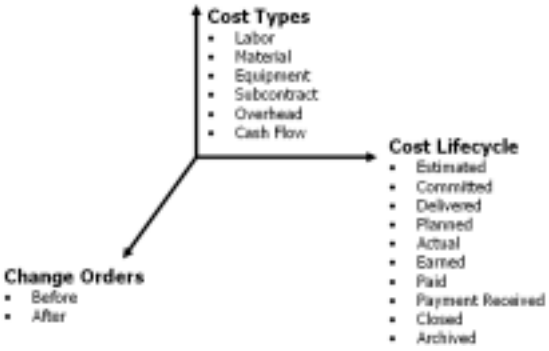

Figure 1. Three Dimensions of Cost Information

Cost Type of a cost item can be one of the six cost types: labor, material, equipment, subcontract, overhead, and cash flow (or payment). On the other hand, the cost item goes through its own *Cost Lifecycle* of estimated, committed, delivered, planned, actual, earned, paid, payment received, closed, and archived stages. The same cost item also can be changed during the construction through *Change Orders*.

2.2 Cost Information Model

A model is a representation of structure. Within the context of this research, a model can be described as a complete mathematical and descriptive representation of an information object and its relationship to other objects. A project information model is a model expressed in terms of the project variables of cost, time, resources, and scope of work [4].

The modeling is used to assist in understanding and communication the requirements for the development of the information system.

2.3 Object-oriented Cost Information Model (OCIM)

The OCIM consists of four modules (layers); Cost Object Layer, Project Layer, Information Output Layer, and External Interface Layer. Figure 2 shows the overall layout of OCIM.

The Cost Object Layer (COL) contains basic cost information consisting of a *Cost Object* (CCostObjectCell), six sub-classes of the cost objects (CLO, CMO, CEO, CSO, COO, and CPO) representing *Cost Type*, and a *Mapping Object* (CCostObjectRoot).

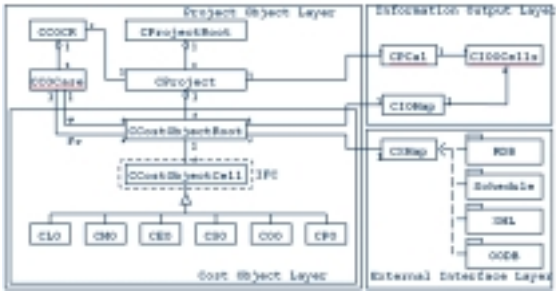

Figure 2. The Overall Layout of OCIM

The Project Object Layer (POL) includes the Cost Object Layer (COL) through the aggregation association between CProject class and CCostObjectRoot class, represented by a line with a diamond symbol at the one end. This is an important relationship because most of the information abstraction occurs here. External programming routines that selectively aggregate cost information according to the user's requirements are implemented in this relationship.

The Information Output Layer (IOL) contains a platform specific graphic output module which simply renders data in chart formats. The classes within this layer associate with the mapping object (CIOMap, or CInformationOutputMap), which relates the Information Output Cell Object class (CIOOCell) to Cost Object class.

The External Interface Layer (EIL) is the gateway of the OCIM to the external systems. The external systems are any database systems, software applications, or information standards over which the OCIM has no direct control. Yet the input from the systems is essential for the model. Some examples of these systems include scheduling systems, estimating software, aecXML, and other corporate financial database systems. A mapping object takes controls the information traffic between external systems and the OCIM, directing it to proper places. Separate data interpreters are necessary to import and export data between the systems.

3 OBJECT-ORIENTED DATABASE FOR COST COMPILATION

3.1 Cost Object Layer

Cost Object (CO) is a general term for the combination of objects in which most of cost related data is defined. It consists of three, hierarchically organized, primary objects: Cost Object Root (COR, i.e. CCostObjectRoot), Cost Object Cell (COC, i.e. CCostObjectCell), and the sub-classes of COC representing six cost types: labor, material, equipment, subcontract, overhead, and payment (i.e. LMESOP).

Figure 3. The Objects in Cost Object Layer

The objects in the Cost Object Layer (COL), COR, COC, and LMESOP, are the core objects of the proposed information model and they are represented in Figure 3. The COL is a complete package of cost data, a module with essential attributes and basic relationship definitions. Also, the data contained within the COL are, in essence, very plain values of cost and date with a very versatile nature. Thus, the COL has great potential as a module that can be plugged into other cost oriented information systems and utilized as a core element of many database systems in the future.

3.2 Project Object Layer

The Project Object Layer (POL) processes the data stored in Cost Object Layer and organizes the information at different abstraction levels. The aggregation association between the CProject and CCostObjectRoot classes is where most of the cost data processing occurs.

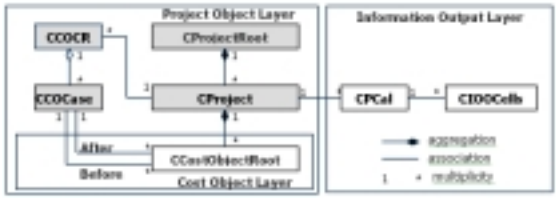

Figure 4. Project Object Layer

As shown in Figure 4, POL contains the objects for change order management. Also, CProject class has an association to CProjectCalendar class to provide the Information Output Layer (IOL) with access to project data.

The Project Object (represented as CProject) is equivalent to a single project and is a class in which the general project data is stored. It has attributes for construction type, project region, project period, and object identification. Some of the cost related data such as project tax rate, markup rate, and project fixed overhead costs also can be stored in this object.

CProject manages change orders through an association with Change Order Case Root (i.e. CChangeOrderCase) object. It also has a direct association to the Information Output Layer.

The Project Root Object (represented as "CProjectRoot") aggregates individual project objects (i.e. CProject) and organizes them into project information by project region and construction type.

Change orders are unavoidable in almost all construction projects. The revenue increase resulting from change orders often contributes to a considerable portion of the entire project revenue. Project managers must expect frequent change orders during any project and be prepared to accommodate the changes into their system from the beginning.

Figure 5. Change Order Object and Its Relationships

As shown in Figure 5, each change order becomes an instance of a Change Order Object (CChangeRoot) which consists of Change Order Case Objects (CChangeCase). A Change Order Case Object is a simple class with two associations, each pointing to a collection of cost objects. CChangeOrderRoot has an association which points to the IfcChangeOrder class. General properties of change orders such as descriptions, note on change reasons, date and time, status, cost estimate, etc. are modeled in the IfcChangeOrder class. IfcChangeOrder class is an externally defined class by the International Alliance of Interoperability [5].

3.3 Information Output Layer

The function of the Information Output Layer (IOL) is to transfer processed information to the user in a graphical format. It stores numeric values in a cell (i.e. computer memory cell) which represents a calendar date. The value stored is then plotted as a value on the vertical axis, with many values forming to form a connected line of graph. There are two objects defined for this operation: Information Output Cell Object and Project Calendar Object. Figure 6 depicts how data from CProject is compiled into Project Calendar Object.

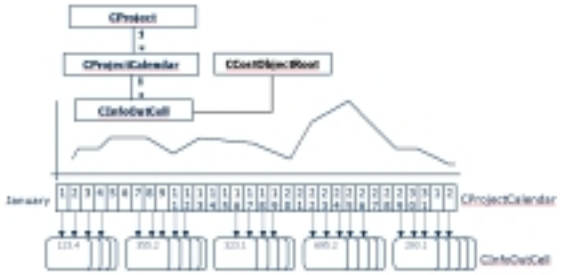

Figure 6. Information Output Layer

In the database, Information Output Cell Object is defined as a class named CInfoOutCell. The CInfoOutCell contains three simple attributes: value, cost type, and information type. Each CInfoOutCell class has two relationship pointers, one to Project Calendar Object (CProjectCalendar) and the other to Cost Object Root (CCostObjectRoot).

Project Calendar Object (CProjectCalendar) is a simple set of objects which represent calendar dates of project duration. Each instance of CProjectCalendar has associations to a number of numeric values (i.e. instances of CInfoOutCell) so that a certain value of a given date can be retrieved directly.

3.4 External Interface Layer

External Interface Layer (EIL) is a group of objects that provides an interface with external systems. It consists of a mapping object (CExternalMap) and an Activity object. The external systems considered for the development of the OCIM are project scheduling systems, corporate managerial database system, the aecXML standards, and IFC standards. An interface with the object-oriented activity object developed by Chin [1] is also built into the layer. Figure 7 depicts the interfaces between CExternalMap and the external systems.

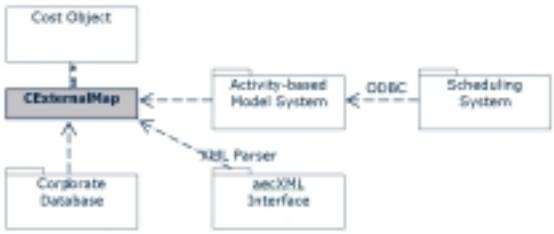

Figure 7. Objects and External Systems in External Interface Layer

3.5 OCIM Information Model

The OCIM is developed upon the criteria specified by the requirements of the management levels. It is important that the designed model is capable of producing the prescribed information. Most of the processes are external of the model itself and implemented as program routines in the prototype system (OCIMPS). The fundamental information retrieval process for this is also described in this section, along with how the information is organized to meet the different requirements of the four management levels. The four management levels are defined as: Operational Manager, Project Manager, Regional Manager, and Top Manager. While an operational manager and a project manager need detailed cost information of a single project (Figure 8), a regional manager and a top manager of the company would want compiled information from multiple projects (Figure 9).

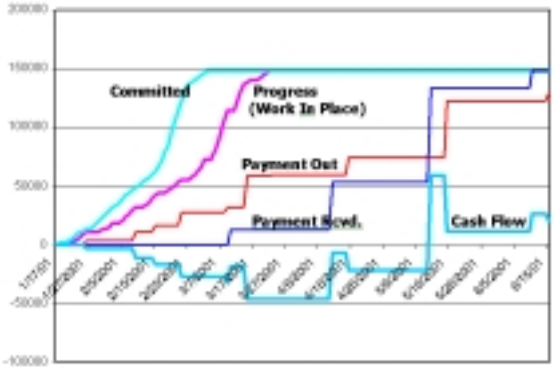

Figure 8. Cash Flow of Single Project

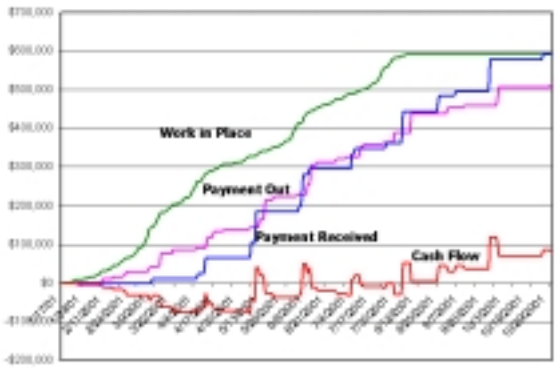

Figure 9. Cash Flow of Multiple Project

The information needed by top managers can be organized by aggregating the instances of CCostObjectCell. For the case of budget trends and forecasting, the instances of *Budgeted (or Planned)* cost are aggregated and organized per month or quarter year.

Figure 10 depicts the process of information retrieval. For Quarter 1 of the year 2004, there are three cost incurring interactions (i.e. instances of CCostObjectCell) of which cost values are at $12,000, $8,000, and $15,200. The total budget of $35,200 for the quarter is organized by the Project Object (CProject) and then passed into Project Calendar Object (CProjectCalendar). The value of $35,200 with the time indexed at Q1/2004 (i.e. the Quarter 1 of

the year 2004) is stored within the output cell (CInfoOutCell) in the Information Output Layer (IOL). By repeating this process, a series of display data sets are prepared in a very compact format. When there is a query from a user requesting "Budget Trend for the Year 2004," the prepared data set is used in the information output.

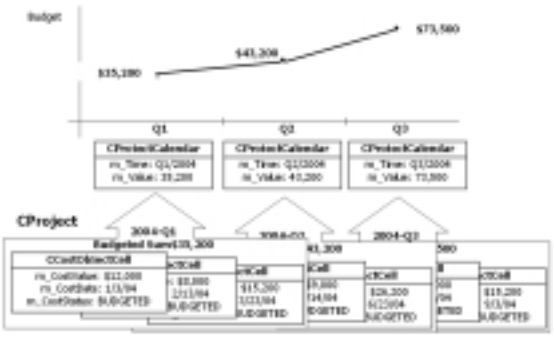

Figure 10. An Example of Information Retrieval Process

3.6 OCIM Prototype System

Based on the information model, a prototype system is developed. It is developed using ObjectStore™ PSE Pro as the object-oriented database engine and C++ language as a tool for developing user interfaces.

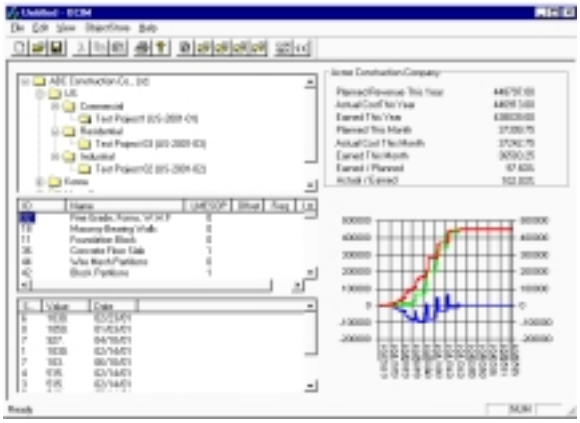

Figure 11. OCIM Prototype System's Main User Interface

While the database management system, ObjectStore PSE, takes care of data maintenance, another module within the prototype system processes the data and provides the output to users. This module refreshes and updates the output data periodically so that the display of the information can be instantaneous. The user may choose a portion or an entire project, a group of projects, or the entire projects of the company depending on his or her user level. Especially for the top management, the amount of data to be processed for a single display will be enormously large and a real-time processing often can be difficult. The prototype system always contains an updated set of data for immediate response to the user's needs. The display data, therefore, will have a certain amount of lag (i.e. 1 day) in terms of how current the data is. However, such lag is widely accepted in construction without too much concern in making managerial decisions. Yet the overhead for maintaining such data is at minimum because the display data consist of simplified numbers and dates.

3.7 Information Abstraction

As described in Section 3.5, four levels of information abstraction have been specified. At the operational level of management, the cost information must be highly detailed and accurate. It must contain every cost related interaction of material, labor, and equipment related expenditures. The collection of such expenditures then can represent the progress of construction activities. The progress of the work packages and ultimately of the entire project can again be derived from the collection of detailed single cost interactions.

Figure 12 through Figure 14 show how the information is organized for different managerial levels. The cash flow profile of one project is prepared for a project manager as shown in Figure 12, while the charts of multiple projects are generated for regional managers in Figure 13 and Figure 14. The corporate level cash flow trend and forecasting can be further generated using similar methods.

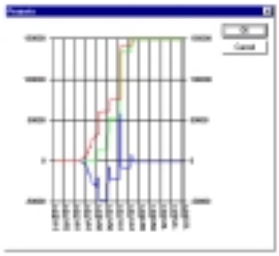

Figure 12. Cash Flow of One Project

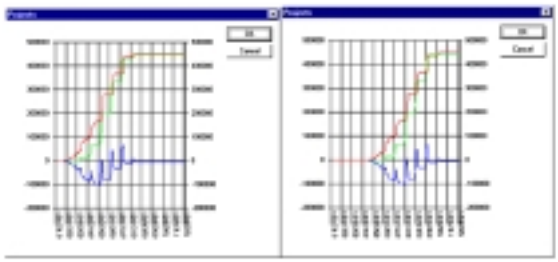

Figure 13. Cash Flows of Regional Projects

Figure 14. Cash Flow of All Projects

4 SUMMARY

The ability of larger construction companies to make corporate decisions in a timely fashion becomes critical to avoid costly corrective actions. The information necessary for making such decisions comes from a large pool of corporate data. In order to efficiently process large amount of data, an information model for multiple project management is essential.

In this research, an information model based on *Cost* is designed and presented. An operable prototype system is developed based on the model using an object-oriented database.

Using the periodical update feature of the prototype system, an immediate access to necessary information by the user is made possible. The different levels of information abstraction are also successfully generated to meet the different requirement of the user of different levels.

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An Application of PDA and Barcode Technology for the Improvement of Information Management in Construction Projects

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ABSTRACT: Work information in a construction project can be effectively used to analyze the project status related to schedule, cost, productivity etc. The purpose of this research is to develop a computer-based system using PDA and barcode technology to measure and monitor the amount of workforce resources and productivity. The developed system is expected to effectively assist schedule planning and management for present and prospective construction projects.

KEYWORDS: PDA, Barcode, ASIMO, Labor management, Productivity, Schedule management

1. INTRODUCTION

Work information can be used to accumulate construction information, analyze project status and management system, and design a new similar project plan. This information can also be used to make productivity data, and these productivity data can be as well used to analyze the relationship between 'as planned' and 'as built' in scheduling management of a project. It is common that site engineers' experience during the project period is a critical factor in terms of collecting and managing a great deal of construction information, but relying on the only site engineers' experience has been an obstacle in the effort to improve construction efficiency and accumulate construction data. Such a condition may be the result of the lack of systems and IT tools for collecting workers' data, which can be directly applied to construction management.

The purpose of this paper is to develop a computer-based system (named 'Advanced Site Information Management Organizer': ASIMO) for measuring and monitoring the amount of workforce resources, work materials, and productivity data by applying PDA and barcode technology. The developed system is expected to assist schedule planning and management effectively for present and prospective construction projects. The scope of this research is limited to structure work in apartment buildings. To make a ASIMO system, this research begins by describing the specific characters of the structure work as well as performing the literature review. The developed ASIMO system is then illustrated in this study. This research validates the effectiveness of the ASIMO system by using data which were collected in construction field. Finally, conclusions are made concerning the value and applicability of the ASIMO system.

2. THEORETICAL CONSIDERATION ON THE INFORMATION MANAGEMENT OF CONSTRUCTION PROJECTS

2.1 The Nature of Structure Work in Apartment Building Construction

Construction of apartment buildings includes works related to the earth, foundation, structure, finishing and others. Among these works, the structure work, as a primary work making up 60% of all processes, is a part of the critical path. The characteristics of the structure work in the construction of apartment buildings include the following.

1) Repetitive activities: The structure work is chiefly composed of vertically repetitive activities. It is thus not difficult to measure and analyze the labor productivity statistically.

2) Composition of diverse activities: The structure work consists of several activities such as the form work, the steel work, the concrete work, which are carried out by specific teams. So, it is possible to measure a worker's productivity in each activity.

3) Limited workspace: In the case of the structure work, it is easy to measure the worker's productivity for each floor of each building because of the characteristics of the construction style, which is

performed vertically, step by step.

Consequently, the division of activities can be easily made, and it can be possible to collect data regarding of workers' working time in each activity and the amount of performed work. In addition, these collected data could be analyzed and could be changed into a variety of historical data.

2.2 Needs for the Information Management in a Construction Project

The construction information management in structure work performed for apartment building construction is widely known to be comparatively easy. However, because a construction plan are formulated by being based on a construction manager's experience rather than on exact historical data, such a plan often has problems such as frequent changes in the resource flow and the schedule. The problems of the information management system in Korean construction projects are summarized in Table 1.

Table 1. Problems of the Information Management System in Korean Construction Projects

Factors	Contents
Lack of documentation system for the construction information management	The existing documents such as daily reports are not usually made timely, and largely depend on a site engineer's experience In addition, most of these documents are generally thrown away after one-time use.
Poor computer-based system	Since most programs for construction management are mainly made only for plan of a new construction project, it is difficult to measure and monitor the actual construction process
Lack of data for the labor and productivity management	Predicting the schedule of each activity requires labor and productivity management data, but both a method to collect these data and a system to analyze them do not exist at the present.
Process focused on only the amount of performed work	To calculate the rate of progress, data such as a worker's working time, the amount of performed work should be considered, but only the amount of performed work is considered in actual construction management.

For solving these problems, the following process is required.

- Determine a method to collect data from each activity during construction.
- Collect data of each activity in the field.
- Calculate the productivity data by applying the data, which are workers' working time and the amount of performed work in a day, collected in each activity.
- link the productivity data with the scheduling management.
- Calculate a variety of productivity figures by using the productivity data.
- Accumulate the historical data for construction management

To collect the productivity data on the time and amount of each activity in the field, the most effective method is using IT tools.

2.3 Current Related Research Issues

There have been major advances in using IT tools to collect data for construction project management over the past few years.

(1) Trend and Application of Korean IT Technology

Kang(1995) developed a system for making a plan and easily managing field inventory by exactly showing the materials and assembly situation. The information on the materials to which a bar-code is attached is input into a computer and then, this information is transmitted through the LAN to a computer in the head office. By this process, a construction manager in the head office can have a good understanding of both the material production process in the factory and the construction process in the field.[1]

Lee(1997) developed a system which can increase the efficiency and speed of works done for construction. The system gives a construction manager the images presenting the progress of construction. A construction manager in the head office can have a good understanding of the construction progress from start to present by watching photographs on a computer screen containing the data on the construction site.[2]

Lim(2000) pointed out the need to change the existing worker checking system. He developed a system which allows a construction manager to recognize the site engineers' and workers' work time. In the system, a bar-code reader, which is installed in a field office, could collect the workers' bar-code data allocated to each of the workers.[3]

(2) Trend and Application of Foreign IT Technology

Calibre2000 (BRE, 2000) proposed a method for measuring the productivity of work and the situation of a construction by using a PDA and a digital camera. These IT tools can be used to collect pictures displaying the progress of performed work and data

on the work duration of workers. Then, by reviewing the data on labor productivity and the performance collected by the IT tools, a construction manager can receive a better understanding about the current construction situation and the productivity of each work.[4]

Lin(2001) proposed a model to support communication between a construction group (e.g. people who are at a construction site, a field office and a head office) and the other groups (e.g. a sub-contractor, a material supplier, a equipment supplier, an owner, an architect and a consultant). This model collects construction site data. These data can be collected by using a PDA.[5] Like the researches and practices illustrated above, although IT tools have been used in construction management over the years, they have still been insufficient in terms of users' convenience, and limited in the number of data targets that must be collected for construction management.

Consequently, this study developed a system for construction management by connecting labor management and productivity management with scheduling management of a construction project and by applying the data collected from IT tools in a construction site. The following data must be collected:

- Workers' time in office and time out of office.
- Workers' working time in each activity.
- The amount of materials used in the work performed daily in each activity.

3. METHODOLOGY

3.1 Methodology to Collect Data in the Construction Site

This paper proposed a methodology, illustrated in Fig. 1, for collecting data in the construction field by using IT tools.

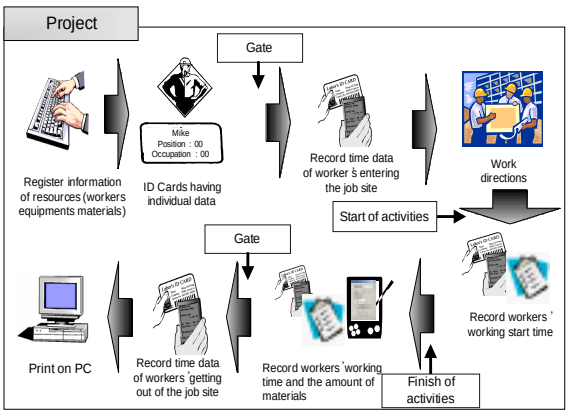

Figure 1. Process for Collecting Data in the Construction Field

To collect data, a site engineer would input a worker's data into a PC on site and provide each worker with a bar-coded ID card. At the beginning of the day, when the workers enter the gate, the barcode would be scanned by a PDA to which a barcode reader is attached. This would give a manager a list of the workers who are on the jobsite and the time when the workers entered the jobsite. An inspector would record the time data related actual working time of each worker in each activity in the PDA. Moreover, at the end of the day, the inspector would record the amount of materials used in the work performed daily in each activity, and the workers would be checked out when the barcode reader scans their barcodes at the exit gate.

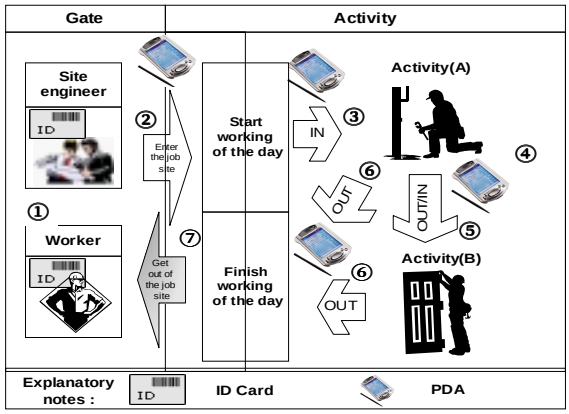

Figure 2. Process for Collecting Data of Workers' Working Time

The data collected through this process would be changed into the data which can be used in the labor, productivity, scheduling management. The detail of the process for collecting data of the workers' working time is illustrated in Fig. 2. First, to collect the data on the time when site managers and workers enter the jobsite, site managers and workers would be provided with ID cards including a barcode(step 1) and then, at the beginning of the day, their barcodes would be scanned by a PDA(step 2). To collect the data on the workers' working time for each activity, the inspector would record the time by using a PDA for the workers when the site manager inputs them into each activity (step 3). At the end of the day, the inspector would also record the time by using the same IT tool (step 4). Moreover, if workers moved among the activities, the inspector could record data of the workers' finish time in the prior activity and start time in the new activity. At the end of the last work of the day, the inspector would record data of the workers' finish time of the last activity (step 5). Lastly, at the end of the day, the time at which the workers' leave the site would be checked out when the barcode reader scans their barcodes at the exit gate (step 6).

3.2 Design of User Interface for PDA

Fig. 3 shows the design of the user interface for PDA to collect the data on workers' jobsite entrance time, working time of activities, and the amount of performed work in each activity. The User interface

in Fig. 3(a) collects the jobsite entrance time data. The site engineer can use the collected data to check the worker's attendance, and the data can be also used to print daily reports. The user interface in Fig. 3(b) is to select the on-going activity of the day. These activity data can be transmitted from a server to the ASIMO system. After the inspector selects the activity of the day on the PDA screen, he would record the data on workers' working time in that activity. At the end of the work, the inspector could directly record the figures on the amount of materials used in the work performed of the day in each activity or input the percentage of the amount. The data collected in this process can be changed in the ASIMO system into fundamental data, which are useful in the labor, productivity, and schedule management.

(a) Collect Time Data of Workers' Attending the Jobsite

(b) Select an Activity

(c) Collect Time Data of Workers' Working

(d) Record the Amount of Performed Work of the Day

Figure 3. User Interface for PDA

4. SYSTEM IMPLEMENTATION

4.1 Surroundings of Implementation for ASIMO System

ASIMO system consists of the DBMS (database management system)-based server, wireless internet-based PDA client and a web-based PC client. The PDA is highly portable and convenient for entering data any where, any time.

Therefore, this IT tool can be the best tool to collect data such as workers' time in office and out of office, the start and finish time of workers' working in each activity, and the amount of materials used in the work performed in each activity. The user Interface of the web based-PC client and PDA were designed so that the user can conveniently access the system under the internet network environment, and the user interface of PDA could be transmitted by wireless LAN in real time. The data transmission in the ASIMO system is shown in Fig. 4.

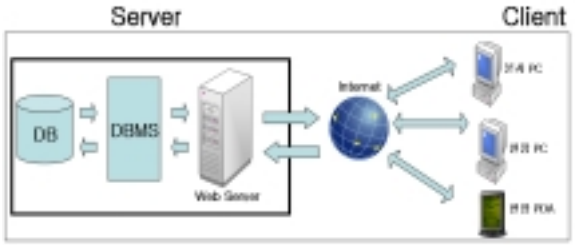

Figure 4. Data Transmission in the ASIMO System

Table 2. shows the developing environment of the ASIMO system.

Table 2. Developing Environment of ASIMO

Sever		OS	Window2000 Sever
		Web Sever	Apache Web Sever
		Database	My SQL
		Language	PHP
Client	PC	OS	Window 98/2000/ME/XP
		Browser	IExplore 4.0/Netscape
	PDA	OS	Window CE/Pocket PC/Palm OS
		Browser	IExplore 4.0/Netscape

4.2 Implementation of the ASIMO System

To verify and test the possibility of application of the ASIMO system to the construction field, the data on 4 apartment buildings on which the structure work was performed were collected and applied to the ASIMO system.

(1) Screen of the Input Module

The input module is a function by which fundamental data can be input to operate the system. Using a PDA, this module can make data collecting easy, and help the printing of the collected data in the other function modules. Fig. 5 shows the input data screen for the planned activities. In this screen, the data such as the planned amount of materials, the planned MH(man-hour), the planned productivity, the planned start and finish date of every activity are entered. Once the construction starts, the planned activity data can be influenced by a variety of factors such as the changes in the work, supply plan and the decline of productivity of the several activities. Site

manager can not use the planned activity data to collect the activity information on the PDA. Shown as Fig. 6, the site engineer should select activities to be performed in the next day by considering the field situation and work plan. These selected data would be displayed on the PDA screen for the user's convenience.

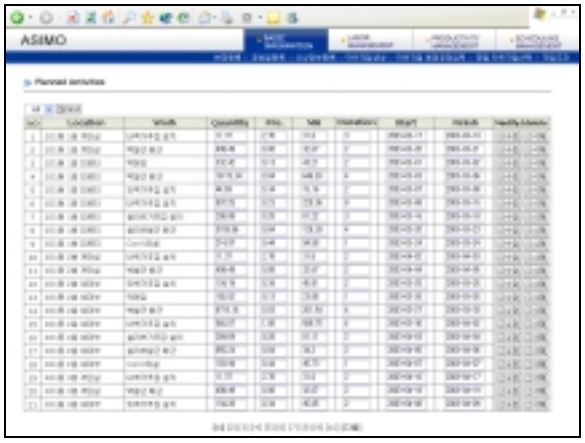

Figure 5. Screen to Input Data of the Planned Activities

Fig. 7 shows the screen for entering a worker's individual data. In this screen, a worker's personal data such as name, company, position, skilled/non-skilled worker, and the barcode number is entered.

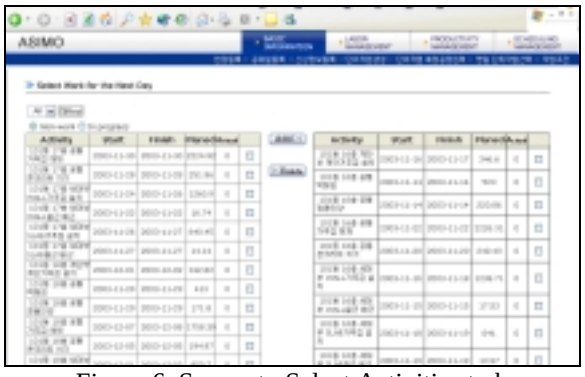

Figure 6. Screen to Select Activities to be Performed Next Day

(2) Screen of the Labor Management Module

Fig. 8 is the screen that shows the status of the workers' time in office and time out of office collected by a PDA. This screen helps the site engineer to identify the workers who have entered the job site within a certain period. Such information can be useful to calculate the labor cost.

Fig. 9 shows the screen the in/out times of the workers in activities performed on a specific date. In this screen, each worker's data such as name, position, type of occupation, the names of the activities in which the worker has worked, and in/out time for the start/ finish for the work performed by the worker can be printed.

These data could also be printed in the productivity and scheduling management module and can be used in the analysis of the result of the project.

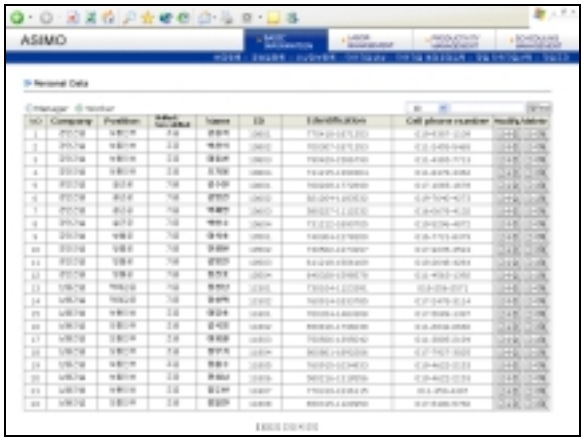

Figure 7. Screen to Input Workers' Individual Data

(3) Screen of the Productivity Management Module

Fig. 10 is the screen showing the productivity data of the activities performed on a specific date. These productivity data can be calculated by using the data on the workers' working time in each activity, and the amount of the performed work. The productivity data can largely be classified into the productivity in an activity (unit/MH) and the actual time worked in an activity(MH/unit). Therefore, as shown in Fig. 10, the productivity in an activity of the wall form work on the house side, the 4th floor, No.101 is 3.12, and the amount of performed work per worker and per hour in an activity is 0.46. The value of 3.12 means that one worker can perform the work on an area of 3.12㎡ for an hour; on the other hand, the 0.32 means that 0.46 man-hour is needed to perform work on an area of 1㎡. Moreover, the inspector can record any productivity problems of an activity in the PDA to provide exact productivity data.

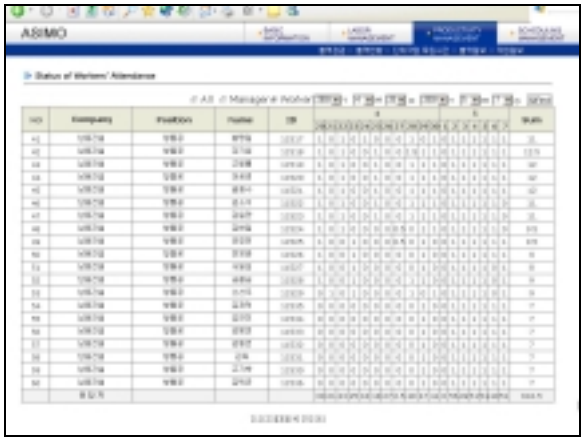

Figure 8. Screen of the Situation of Workers' Attending Time within a Certain Period

The productivity data can be accumulated and output according to various criteria such as the activity, the building, and the floor. Such data would be useful in the productivity analysis and final

project assessment.

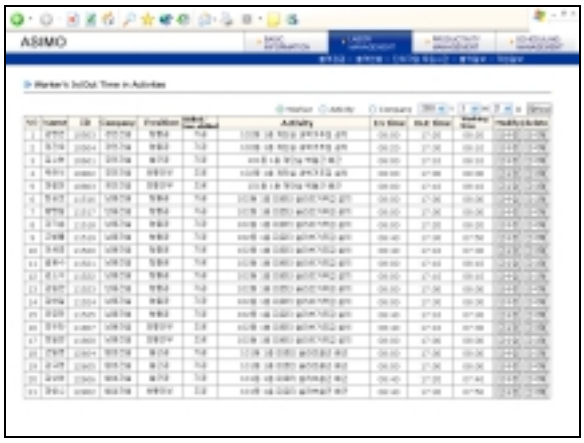

Figure 9. Screen of the Situation of Workers' In/Out Time in Each Activity

(4) Screen of the Scheduling Management Module

In the scheduling management module of the ASIMO system, the historical data for scheduling management and the rate of progress can be represented by applying data on the workers' working time, the amount of performed work, and the productivity related to the activities. Fig. 11 shows the screen of the historical data for scheduling management. The data printed on this screen are the planned start/finish date, the actual start/finish date, the planned amount of work, the actual amount of performed work, the anticipated duration, and the variation of the actual duration regarding every performed activity. These data, calculated by applying the relationship between the data on the workers' working time and the amount of performed work collected from the PDA, could be used as supporting data in actual scheduling management.

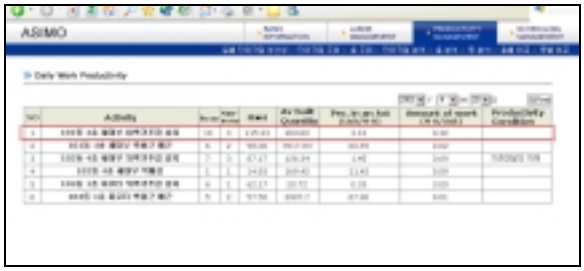

Figure 10. Screen of the Productivity of Activities Performed on Specific Date

The rate of progress represents the percent (%) of the working process. To calculate the rate of progress, the following process is required.

- Calculate a worker's working time by an activity (the planned amount of work in an activity × the planned duration of work in an activity(MH/unit)).
- Sum up the work durations for the activities by floors and buildings.
- Assign a weighted value to each activity regarding the rate of work duration in an activity to the sum of work durations for activities, by floors and buildings.
- Calculate the rate of progress(the weighted value × the amount performed work).

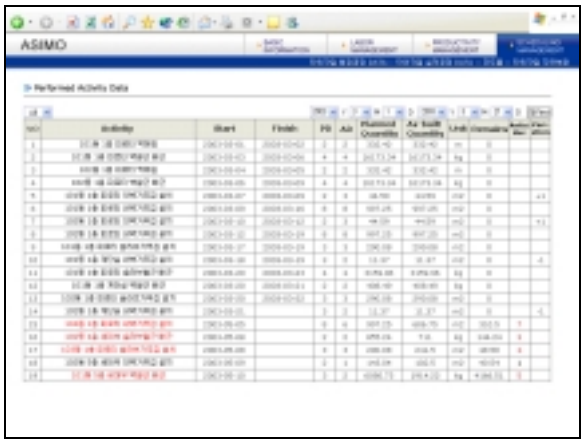

Figure 11. Screen of the Historical Data for the Scheduling Managment

Fig. 12 shows the screen of the progress rate for buildings. This screen illustrates that on April 28, the progress rate of the work on the fourth floor, No.101, is 40.89% and that in this building is 34.13%. Therefore, progress rate data can be useful for the site engineer to easily understand the work progress status by floors and buildings.

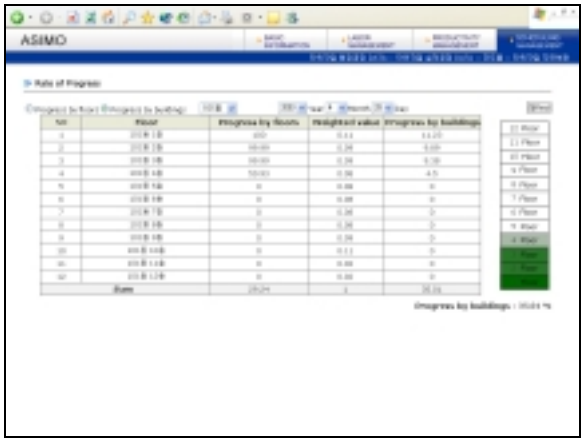

Figure 12. Screen of the Rate of Progress by Buildings

5. CONCLUSION

The ASIMO system developed through this research can collect data on the worker's time in office and time out of office, the workers' working time input in activities as well as the amount of work performed in a day. These data can not be only historical data, which could be applied in the labor, productivity, scheduling management, but also important data which could be used to analyze the result of project management. Furthermore, the ASIMO system would be better than the existing system because the ASIMO system is more accurate

in analyzing a situation, comparing 'as planned' with 'as built' of the construction project and providing similar future projects with useful data. In this paper, the conclusions are as follows:

1) To find problems and to present a solution related to the structure work of an apartment buildings, several interviews with site managers were performed. Important factors to collect and analyze data on the worker's time in office and time out of office, the workers' working time input in activities and the amount of work performed in a day were determined.

2) A methodology based on IT tools such as the PDA and barcode has been proposed to collect data on workers' working time in each activity and the amount of performed work.

3) An algorithm, which is based on the data on workers' attendance, working time in each activity, and the amount of performed work, was developed to integrate the management of labor, productivity and scheduling. The ASIMO system has been developed by designing the UI on the PDA and the PC, which was implemented on the basis of the database modeling.

4) The data of 4 apartment buildings on which the structure work had been performed were collected and the result of application of the field data shows that the developed ASIMO system is useful for construction management (labor management, productivity management, scheduling management).

Acknowledgements

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EXPLORING THE MONEY LEFT ON TABLE FOR CONSTRUCTION PROCUREMENT NEGOTIATION

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Abstract: Most contractors negotiate with suppliers for their construction procurement according to negotiators' experiences instead of extensive exploration of negotiable options and negotiators' preferences. Consequently, negotiators often reach suboptimal agreements, and leave money on the table. This research developed an agent-based computer system that find optimal agreements using the genetic algorithm, compared the results with the actual contractual agreements, and determine the "money" left on the table in the traditional construction negotiation.

Keywords: intelligent agent, genetic algorithm, e-commerce, artificial intelligence, construction management

1. INTRODUCTION

Negotiation is commonly required in the procurement of construction materials to reach the final contractual agreement. For a construction procurement item, a general contractor typically solicits several price quotations from suppliers, considers the suppliers' performance, evaluates those quotations, and narrows down a few prospective suppliers. Subsequent process often involves formal or informal negotiations between the general contractor and the prospective suppliers to finalize the price and other contractual terms (e.g., payment by 30-day check or 60-day check, and payment calculated monthly or at completion).

Nevertheless, a general contractor needs to limit the number of prospective suppliers to negotiate with and the number of negotiation meetings because of the time and man-hours involved. As a result, the negotiation agreement is usually reached depending on experience instead of extensive exploration of negotiable options and preferences of negotiating parties. As concluded by Raiffa [16], even in simple negotiations, people often reach suboptimal agreements, thereby "leaving money on the table". The challenge of negotiation arises, in part, from the fact that each side has private information about their own utility function but is ignorant of the other's values and strategies. [14]

This research developed an agent-based computer system that find optimal agreements using the genetic algorithm, compared the results with the actual contractual agreements, and determine the "money" left on the table in the typical construction negotiation. Negotiators involved in three procurement items (i.e., pre-mixed concrete, rebar, and rebar laborer) of two plant-office complex projects participated the experiments.

2. LITERATURE REVIEW

Negotiation is a process for resolving conflicts between two or more parties [2]. Ali [1] investigated the factors that suppliers might consider when submitting a bid to a general contractor, including prompt payment habit, reputation for shopping after contract award, experience in building similar projects, efforts in planning and supervision, financial capacity, reputation for finishing projects on time, other work opportunity, and chance to get job of the contractor, past experience with the contractor, clarity of work's specifications, terms of general contract, construction schedule, and construction methods used. Many of these factors (e.g., reputation for shopping after contract award and experience in building similar projects of the contractor), despite being important for preparing the bid proposal, are unlikely to appear as an issue in the negotiation process.

Mumpower [12] found that each negotiating party perceived the negotiable issues differently, and the perception of an issue might be represented by a function of judgment of utility, including weight, function forms, and organization of joint utility structure. Decision-support research has focused on the design and development of tools for aiding negotiators in various domains such as Genie [8] that stresses model visualization capabilities, NEGOPLAN [10] that generates if-then production rules, and GBML [11] that discovers rules for better negotiations.

Software agents are also employed to facilitate negotiation. Software agents are computer programs that exhibit a certain degree of autonomy. They are continuously active and interact with other systems

on behalf of the user [4]. Nwana [13] divided agents into collaborative agents, learning agents, interface agents, and smart agents. Brenner [5] divided agents into three categories according to their tasks: information agents who search, filter, analyze, and present information; cooperation agents who solve complex problems by cooperating with other agents, humans, or external resources; and transaction agents who execute and monitor transactions.

Snadholm and Lesser [17] found that cooperative agents often exist and perform tasks inside an enterprise such as production planning and meeting scheduling. A competitive agent will not give in unless it can receive comparable compensation during negotiation because it cares only its own benefit and is least concerned with joint benefit. However, such competitive style prevents disclosure of individual preferences and often results in individual loss of benefit. Many electronic commerce (EC) web sites such as OnSale [15], eBay's Auction Web [7], Kasbah [9], and Auction Bot [3] also offer agents that help on-line negotiation on price. For example, Kasbah adopts the distribution type of negotiation and allows users to define their own agents with buying strategies (i.e., anxious, cool-head and frugal), selling strategies (i.e., anxious, cool-head and greedy), and initialization parameters (e.g., asking price, acceptable price, and deadline). T@T [18], in addition to price, allows both buyer and sellers to customize their agents and negotiate on warranty, delivery time and method, service plan, return policy, and free bonus. No agents have been developed to specifically help negotiation of construction procurement between contractor and suppliers.

This research chooses the agent-based approach, and assumes an integration type of negotiation; i.e., enlarging the pie of available resources. Each agent has its own preferences and negotiates with each other through collaboration. However, to be realistic, a negotiating agent is not aware of the preferences of the other, and is communicating through an intermediate coordinator agent.

3. NEGOTIATION AGREEMENT POINTS

In practice, issues to be negotiated are determined at the beginning of negotiations, but new issues sometimes may arise during negotiations. The contractor proposes desired options for the negotiable issues, and the supplier proposes a price according to these options. The proposed price may be continuously lowered during the negotiations. The supplier may also request to modify terms or to include new issues to offset price decreases. The negotiation ends when both parties agree on the options and price.

Dzeng and Lin [18] have conducted a survey to identify key negotiable issues that may arise during construction material procurement negotiations. Key issues identified included *price*, *payment term*, *payment period*, *advance payment*, *resource provision*, *freightage*, *delivery*, and *opportunities* for *extended procurement*, *mass procurement*, and *future procurement*.

These issues may be classified into four categories according to the range of options available. The first category is *price*, for which options lie on a continuous spectrum.

The second category includes issues for which a limited number of commonly used options exist. For example, options for *payment terms* include: “cash”, “30-day check”, “45-day check”, and “60-day check”; for *payment period* options include “on delivery”, “on completion of milestones”, “on completion”, “monthly”, and “bi-weekly”; for *advance payment* options include “10%”, “15%”, “20%”, “25%”, and “30%”; for *freightage* options include “included” and “excluded”, for *delivery* options include “single delivery”, “multiple deliveries”, and “on-call delivery”.

The third category includes issues whose options are a list of items and quantities. For example, options for *resource provision* are a list of provided resources and quantities, and options for *extended procurement opportunities* are a list of additional procured items and their quantities.

The fourth category includes issues for which options are quantity related. For example, options for *mass procurement opportunity* are the maximum quantities procurable; and options for *future procurement opportunity* are possible future procurement quantities. The implied procured item for these issues is the item being negotiated on.

Among the issues identified, only the first and second categories are considered negotiable in this study. Issues of the third and fourth categories are not considered because they mainly arise in a negotiation out of capacity leeway of a contractor and are wholly determined by the contractor. For example, a contractor only offers an opportunity for extended procurement to a supplier when there is still extended procurement that has not been tendered. It is uncommon for a supplier to make a contractor to squeeze out new procurement during the negotiation. As a result, these issues are treated as non-negotiable issues and are determined solely by a contractor.

The non-negotiable issues, although cannot be counter-offered by a supplier, may affect a supplier’s quoted price. Because these issues involve uncertainty, they are represented by estimated

expected monetary values in this research.

3. OPTIMAL NEGOTIATION AGREEMENT

Negotiation can be viewed as a process of seeking an agreement point in a multidimensional space. Each dimension corresponds to a negotiable issue, and can be discrete or real-valued. Each issue may have several options. Each negotiating party values these options differently, and a multidimensional payoff function exists over the space of possible agreement points. Payoff of an option with respect to a negotiator represents the negotiator's preference (or utility) over the option. This study uses the weighted payoff function to measure the goodness of a negotiation agreement.

Suppose n negotiable issues exist, where an offer x can be represented using an array $[x_1, x_2, \ldots, x_n]$, where x_i denotes the chosen option for issue i. The payoff of a negotiator for a particular offer x can be represented as follows.

$$U(x) = \sum_{i=1}^{n} W_i U_i(x_i) \quad (1)$$

$U(x)$: total payoff of a negotiator for the chosen set of options x;
$U_i(x_i)$: issue payoff of a negotiator for the chosen option x_i for issue i;
W_i: weight of issue i for calculating negotiator payoff.

According to this concept, simplified, generalized contractor and supplier payoff functions used in this study are discussed below for the aforementioned two categories of negotiable issues.

Negotiator payoff may positively correlates with issue options. For example, the contractor generally prefers longer *payment term*, in order to delay the payment as long as possible, and thus contractor's payoff for "60-day check" is greater than that of "cash". Negotiators may also feel indifferent to some intermediate options. For example, some contractors may be indifferent to a payment term of "30-day check" or "45-day check". Similarly, a negotiator's payoff may also negatively correlate with issue options. For example, a supplier may prefer shorter *payment term*, and thus may have a smaller payoff for "60-day check" than for "cash". Of course, some suppliers may also feel indifferent to the length of *payment term*.

4. System Description

The system comprises three agents, namely *Contractor*, *Supplier*, and *Coordinator*. The human contractor must initiate the agent with a set of negotiation criteria (i.e., negotiable issues and their allowable options, weights and payoff functions) and GA settings (i.e., population size n, crossover rate c, mutation rate m, and threshold for fitness improvement factor g). Information on the negotiation criteria and GA settings is passed to *Coordinator*, but not to *Supplier*, except for the negotiable issues and allowable options, which are passed further to *Supplier*. The human supplier must respond to this message by determining acceptable options, weight, and payoff function for each negotiable issue.

Contractor and *Supplier* have similar objectives; i.e., to generate an offer that is acceptable to its own criteria and has payoff higher than the offer proposed by the counter part through a continuously random selection process, and evolve the offer to find the best one through GA. Take *Contractor* as an example, the first step is to generate n offers as its population. Each offer includes an option for each negotiable issue and a threshold T, which equals the corresponding payoff of the option according to the payoff function of the contractor. The threshold represents the satisfaction level of the contractor with the offer. The second step involves randomly selecting an offer from the population and submitting it to *Coordinator*, who at this time also receives an offer from *Supplier*. If the offer of *Contractor* provides *Supplier* with a payoff higher than that from the *Supplier* offer, and *Supplier* offer provides *Contractor* a payoff higher than the payoff of the *Contractor* offer, both offers are saved in their respective tentative pools. Otherwise, *Coordinator* passes the offer back to *Contractor* and *Supplier* and asks them to select another offer. This process continues until *Coordinator* has *n Contractor* offers and *n Supplier* offers. The total of *2n* offers are used to calculate the fitness evolution improvement factor g. If g is smaller than the pre-determined threshold, the search has reached a convergence, and *Coordinator* presents the offer with the highest sum of payoff of both contractor and supplier as the final result. Otherwise, *Coordinator* requests both *Contractor* and *Supplier* to generate another generation of offer populations. Through generations of evolution, when g is below the threshold, most offers in the population already have fitness scores approaching the best offer. Thus, further evolution achieves insignificant improvement, and so evolution can stop.

5. EXPERIMENT METHODOLOGY

This study conducted experiments to find the payoff left on the table of construction negotiating parties. Three procurement items, namely pre-mixed concrete, rebar, and rebar assembly, of two projects A and B were selected for the experiments. Both projects involved an office-plant complex. Project A is a $US 7.77 millions project that has five stories plus one underground story, while Project B is a $US 22.79

millions project that has five stories plus two underground stories. The negotiators originally involved in the contracts were invited to assign the utility weights for the relevant negotiable issues and options in C-Negotiator. The negotiators included the section manager of the participating contractor, and the owner, president or vice president of the subcontractors, with from 9 to 21 years of procurement experience.

The actual contractual agreement was taken as the outcome of human negotiations while the agreement suggested by the C-Negotiators was assumed to be theoretically optimal outcome. Because human negotiators may not accept the best agreement suggested by C-Negotiators, the following best agreement that was acceptable to human negotiators was the actual optimal outcome.

The parameter values used for GA were based on the suggestions proposed by DeJong, and included population size = 50, crossover rate = 0.7, and mutation rate = 0.02. The threshold for the fitness improvement factor was set to 5%. A virtual project was also used to help participants familiarize themselves with the system before the experiments began.

6. EXPERIMENT RESULTS

Table 1 compares the negotiation outcomes of contractual agreement (i.e., human negotiation), theoretical optimal agreement (i.e., the best agreement found by C-Negotiators), and the practical optimal (i.e., the agreement chosen by negotiators from the best 10 agreements found by C-Negotiators) for three suppliers, PMC (pre-mixed concrete), REB (re-bar), and RLB (re-bar labor) of both projects. Each set of outcomes includes a joint payoff as well as contractor's and supplier's individual payoffs.

C-negotiators always reached an agreement with higher joint payoff (from 1.1% more to 9.8% more) than human-based negotiation. This difference occurred because the human negotiators tried to reach a mutually acceptable agreement according to experience, while the agents tried to maximize the joint payoff through extensive search. Thus, agents are more motivated in finding the best agreement.

The improvement in joint payoff was smaller than expected. This phenomenon occurred because the number of negotiable issues and options were limited, and human negotiators could reach good agreement depending on years of experience. Nevertheless, the experiments also demonstrated that C-Negotiator occasionally might help negotiators “leave less money on the table”, achieving improvements of as much as 9.8% of payoff, as in the negotiation with re-bar supplier for Project B (Table 1).

Agent-based negotiation does not always reach an agreement with higher contractor payoff or supplier payoff than human-based negotiation. While agent-based negotiation attempts to find the agreement with the highest joint payoff, it may also indirectly redistribute the payoff between contractor and supplier. Therefore, one may not accept the agent-suggested best agreement if his/her payoff is lower than the payoff of human-based negotiation. The remedy to this problem presented here was to choose the agent-suggested 10 best offers, and present only those offers with individual payoffs equal to or higher than those of human-based negotiation. Negotiators found acceptable agreements from the presented ones in most cases. When none of the presented agreements was acceptable, the negotiators might adjust some terms to reflect their concerns.

Table 1 Negotiation outcomes of the experiments

		Con-tractual	Theo-rectical Optimal	Improve-ment%	Practical Optimal	Improve-ment%
			Project-A			
PMC	**Joint**	**146.0**	**147.5**	**1.1%**	**147.0**	**0.7%**
	Contractor	72.0	68.0	-5.5%	70.0	-2.7%
	Supplier	74.0	79.5	7.5%	77.0	4.1%
REB	**Joint**	**153.9**	**165.0**	**7.3%**	**165.0**	**7.3%**
	Contractor	85.3	92.5	8.5%	92.5	8.5%
	Supplier	68.6	72.5	5.7%	72.5	5.7%
RLB	**Joint**	**146.7**	**149.0**	**1.5%**	**149.0**	**1.5%**
	Contractor	72.0	87.0	20.8%	75.0	-4.2%
	Supplier	74.7	62.0	-17.0%	74.7	-1.0%
			Project-B			
PMC	**Joint**	**154.3**	**158.0**	**2.4%**	**157.8**	**2.2%**
	Contractor	90.7	84.0	-7.4%	90.3	-0.5%
	Supplier	63.6	74.0	16.4%	67.5	6.1%
REB	**Joint**	**150.6**	**165.4**	**9.8%**	**165.4**	**9.8%**
	Contractor	86.3	86.4	0.2%	86.4	0.2%
	Supplier	64.4	79.0	22.8%	79.0	22.8%
RLB	**Joint**	**137.0**	**139.5**	**1.8%**	**138.0**	**0.7%**
	Contractor	73.0	85.5	17.1%	75.0	2.7%
	Supplier	64.0	54.0	-15.6%	63.0	-1.6%

Discussion

Figures 1-3 compares the improvement of joint payoff, contractor's payoff, and supplier's payoff of C-Negotiators' suggested best agreement (theoretical best) and the agreement actually chosen by negotiators (actual best). In the Y-axis, the first letter represents the project (e.g., A- for Project A) and the following three letters represent the contract (e.g., RLB for rebar labor). Figure 1 shows that the theoretical best improves the joint payoff by approximately from 1% to 10%. However, negotiators may not always agree to those values, as shown by B-RLB, B-PMC, and A-PMC.

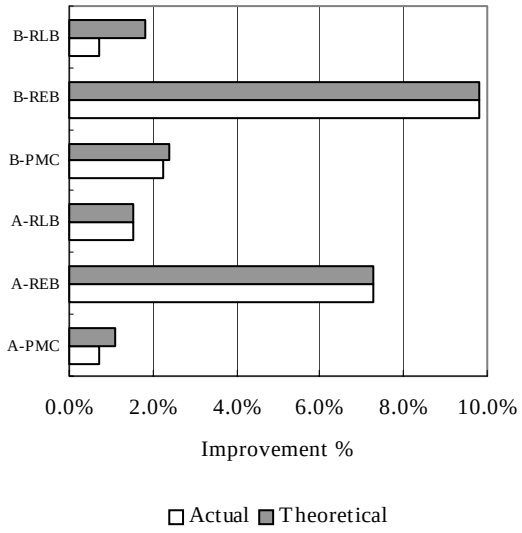

Figure 1 C-Negotiators' improvement on the joint payoff

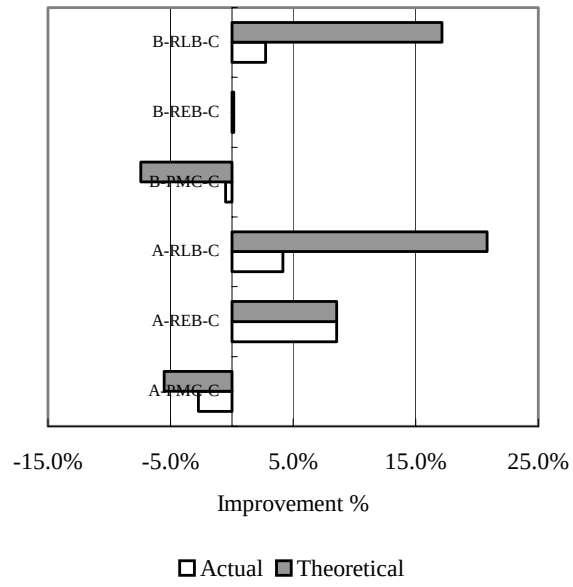

Figure 2 C-Negotiators' improvement on contractor's payoff

Figures 2 and 3 show that, when C-Negotiators was improving the joint payoffs, the improvement on both contractor's and supplier's payoffs was not guaranteed. This also resulted in greater difference in the payoff improvements of actual best and theoretical agreements, as shown by B-RLB, B-PMC, A-RLB, and A-PMC in Figures 2 and 3. In other words, when C-Negotiators suggest the best agreement, negotiators will accept only if the agreement results in better or equal payoff than the contractual agreement, and the proportion of contractor's and supplier's payoff in the joint payoff did not considerably deviate from that of the contractual agreement.

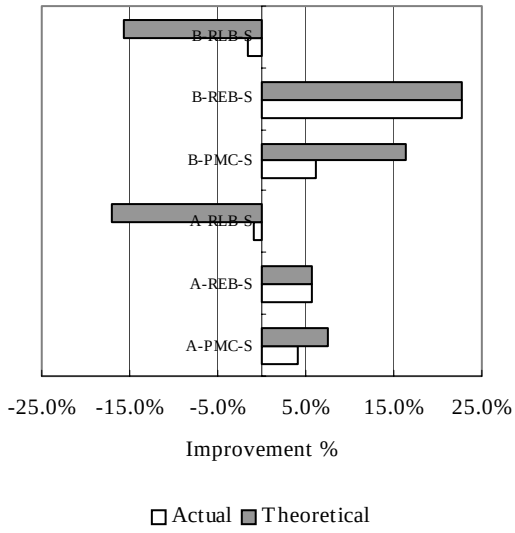

Figure 3 C-Negotiators' improvement on supplier's payoff

However, unlike we have hindsight in these experiments regarding the contractual agreements, in actual negotiation, no one knows the contractual agreement at the time of negotiation. Therefore, even though C-Negotiator's algorithm can be adapted to keep the proportion to accommodate the bargaining power issue, appropriate proportion is hard to determine. Past contracts may be a clue to discovering such a proportion. The future direction of this research will focus on addressing this problem.

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AN ESTIMATING METHOD OF WORKER'S TASK WITH 6-DOF SENSORS

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Abstract: Recently construction workers tend to work alone and are getting older. In such working atmosphere, monitoring their works at the site is necessary for keeping task performance quality and accuracy. However, the management and evaluation of workers' performance can only be done by supervisors' physical observation. Understanding of their works will be easier if the data that shows what kind of task is performed can be estimated from their body positions and movement, and that enable monitoring by data obtained concurrently.

Data for body positions and movements of workers was obtained and measured by using 6-DOF motion sensors, and the method to estimate the type of task by using neural network is described. Finally the authors developed the method to monitor the work at the site using the data obtained by 6-DOF motion sensors and systemized the estimation procedure.

Keywords: 6-DOF sensor, estimation, worker's task, monitoring

1. INTRODUCTION

In recent years, because of high demand of efficient use of human resource, workers tend to work alone. Moreover, workers are getting older, so possibility of accident at site during work time arises in concern. Tasks done by single worker are expected to increase. In such working atmosphere, continuous monitoring of each of worker's action is necessary in order to maintain high quality of performance management. But evaluation of works have been able to only be made by supervisors' physical observation, and it is impossible to understand workers concurrent performance all over the construction site at once.

Site management becomes more efficient by gathering and evaluating data obtained from monitoring workers. The date collected from monitoring shows various positions and movements of workers' tasks. Moreover, the systematic process established for evaluation of collected data should become the method of concurrent monitoring.

The analysis of on-site construction works is made by many. Tamura [1] suggested suitability of improved therblig to the construction works. Mine [2] suggested the method of measuring working time on reinforced concrete placement work and presented time study evaluation result. Kobayashi [3] worked on research for symptoms of worker fatigue in chimney construction. Kano [4] developed five evaluation models for selecting among alternate methods based on past construction records and studied the reliability of the models.

The authors [5] have suggested the method to measure positions and movements of workers and develop into 6-DOF data to estimate workers' task and showed effectiveness of the method.

The objective of this research is to develop automated estimation process, and system for monitoring works real time. Prototype was made based on the developed system and experiment are undertaken for reliability of the system to examine effectiveness of the system. In addition, suitability of use of this device and program for various workers are tested.

2. MONITORING SYSTEM DESIGN

Monitoring system design is composed by 5 parts: 1) Collection of the body position and movement data, 2) Computation of the feature parameters, 3) Calculation for the neural network outputs, 4) Selection of the type of task, 5) Monitoring of the selected task in each time unit, as in Figure 1, according to the method to estimate worker's task.

The design is intended to collect data and output the estimated result. At first, the body position and movement data is collected from three 6-DOF sensors and forms a list. Then some part of the data in the list is extracted for designated time period and used for computation of feature parameters. The parameter is used as input for neural network, and recognized value, output, is derived throughout the calculation.

Process of monitoring system starts from Data collection from 6-DOF. Three 6-DOF sensors are used to collect data and establish list. Then at calculation of recognition value, the data is extracted from the list by designated time interval and find out feature parameters. Using these parameters as input

for neural network, and develop recognition value as output. At making list of recognition value, recognition value is taken for various unit times into the list. Finally at Evaluation of overall selection of task, mean value and standard deviation for recognition value are calculated and compared for each task, then examine the content of works to establish the final estimated result.

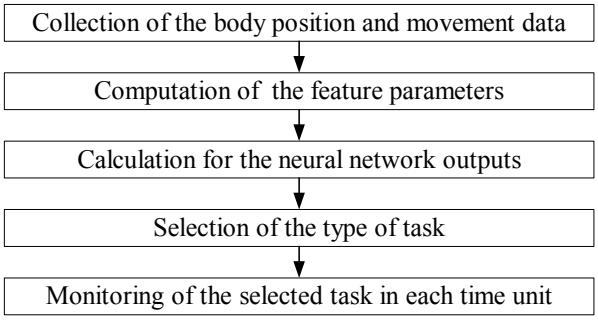

Figure 1. Monitoring system flow

3. ESTIMATION OF WORKER'S TASK

3.1 COLLECTION OF THE BODY POSITION AND MOVEMENT DATA FROM 6-DOF MOTION SENSORS

The sensors in navigation of robots and unmanned vehicles was used to collect 6-DOF data of body position and movement. (Table 1) 6-DOF data composed by 3-axis accelerations and 3-axis orientation in 3 dimensions. (Figure 2)

Table 1. 6-DOF sensor specification

Component	3 accelerometer sensors 3 magnetometer sensors 3 rate gyroscope sensors
Weight	40g
Size	64mm by 90mm by 25mm
Output Data Rate	20Hz
Supply Voltage	9 vdc
Connectors	RS-485

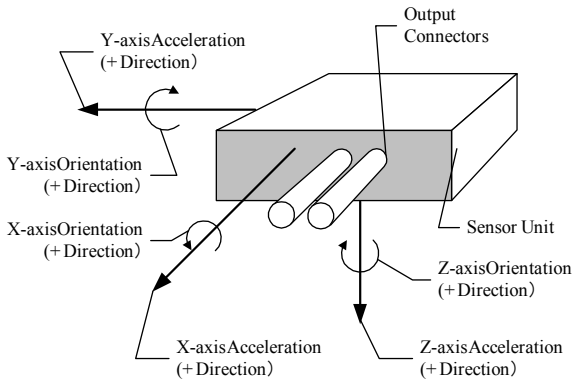

Figure 2. 6-DOF sensor coordinates

Figure 3. Device of monitoring system

The authors examined the body parts for equipments, the 6-DOF sensors. And the body parts were determined as three places: head, arm, leg, for the following reasons.

a. The positions which data can be acquired for the feature of a working posture as 6-DOF data.
b. The positions which sensors do not interfere worker's tasks.
c. The positions which wearing and removal of the sensors in the work site are easy.

The head sensor is fixed on the helmet with the bolts, and the data for changes of position of head from bending and stretching back or twisting the body is collected. The arm sensor is attached with the Velcro tape on the wrist of a dominant hand, and the data for arm, such as operation of a tool and handling parts, is collected. The leg sensor is fixed to the stand attached above right ankle with the bolts, and the data for leg, such as walking, sitting down, stepping on something, is collected. (Figure 3)

3.2 COMPUTATION OF FEATURE PARAMETERS

The data collected from 6-DOF sensors include value of angle changed from movement of the worker's body. Therefore, if a worker's body rotates, the data inputted becomes a value which is different from previous one even if the same type of task is being done. However, when worker is doing the same task, different value may be derived if the worker is facing to the different direction. Accuracy of the estimate improves by use of the data which the effect by the body direction was removed.

Table 2. Feature parameters

Feature Parameters	Equation	Definition	Index
$Avr(H_{(A-B)_i})$	$\frac{\sum_{i=1}^{i=n} H_{(A-B)_i}}{n}$ (1)	Mean value of correlation of sensor-A orientation and sensor-B orientation	$Avr(H_{(A-B)_i})$: Mean of the variables $H_{(A-B)_i}$ $Std(H_{(A-B)_i})$: Standard deviation of variables $H_{(A-B)_i}$ $Sy(H_{(A-B)_{i+1}} - H_{(A-B)_i})$: Sum of the variables$(H_{(A-B)_{i+1}} - H_{(A-B)_i})^2$ $Sy(T_{(A)_i})$: Sum of variables $(T_{(A)_i})^2$ $H_{(A-B)_i}$: Difference of orientation between sensor - A to sensor - B at time(i) $T_{(A)_i}$: Differenc of acceleration from time(i) to time(i + 1) n : Numbers of output data i : Time of data ouput (i = 1,2,$\cdots$, n) A, B : Name of two sensors
$Std(H_{(A-B)_i})$	$\sqrt{\frac{n\sum_{i=1}^{i=n}(H_{(A-B)_i})^2 - \left(\sum_{i=1}^{i=n} H_{(A-B)_i}\right)^2}{n^2}}$ (2)	Standard deviation of correlation of sensor-A orientation and sensor-B orientation	
$Sy(H_{(A-B)_{i+1}} - H_{(A-B)_i})$	$\sum_{i=1}^{i=n}(H_{(A-B)_{i+1}} - H_{(A-B)_i})^2$ (3)	Variation of correlation of sensor-A orientation and sensor-B orientation	
$Sy(T_{(A)_i})$	$\sum_{i=1}^{i=n}(T_{(A)_i})^2$ (4)	Variation of velocity of sensor-A	

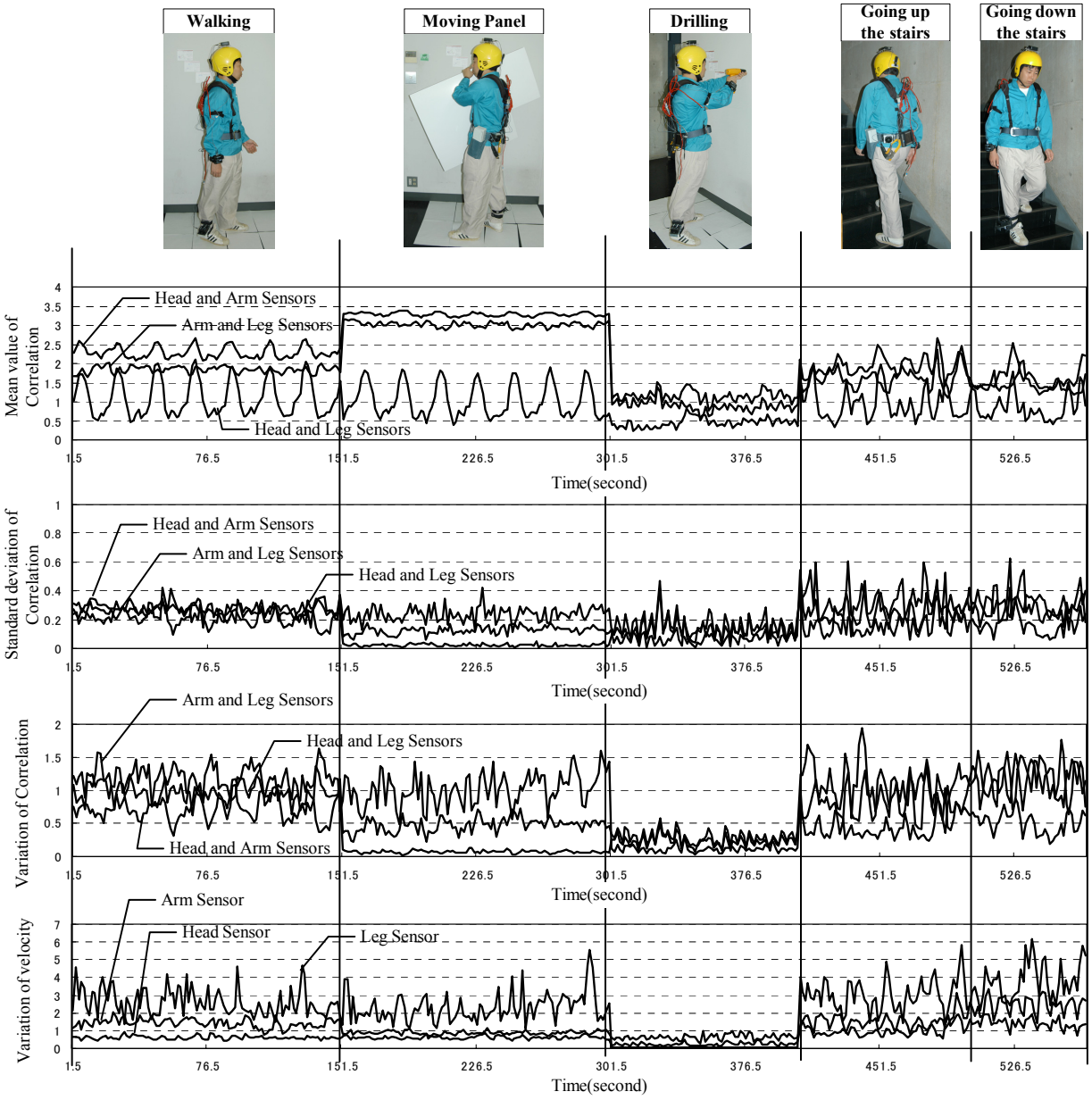

Figure 4. An example of the computed feature parameters (time unit is 1.5sec.)

In order to remove such effect, the authors computed feature parameters according to the relationship between 6-DOF data and body position and movement.

Feature parameters are the mean value of correlation of sensor-A orientation and sensor-B orientation in each time unit computed using 3-axis orientation data Eq. (1), the standard deviation Eq. (2), and the variation Eq. (3), and are the variation of velocity of sensor-A in each time unit computed using 3-axis acceleration data Eq. (4). (Table 2)

Correlation of orientation between sensor-A and sensor-B is inner product of unit vector for sensor-A and sensor-B ($H_{(A\text{-}B)i}$). Three-axis orientation data is translated into unit vector in 3-dimensional position coordinates. Feature parameters are computed by using product of inner vectors.

The mean value of the inner product of unit vector for sensor-A and sensor-B in each time unit ($Avr(H_{(A\text{-}B)i})$), standard deviation ($Std(H_{(A\text{-}B)i})$), and the sum of squared difference value from time(i) to time($i+1$) ($Sy(H_{(A\text{-}B)i+1}\text{-}H_{(A\text{-}B)i})$) are feature parameters.

The variation of velocity of sensor-A is difference of accelerations from time(i) to time($i+1$). The sum of squared value ($Sy(T_{(A)i})$) is another feature parameter.

"Walking", "Moving panel", "Drilling", "going up the stairs", and "going down stairs" were used as experimental work. Then the feature parameters of 6-DOF data were collected. The result was plotted in figures (Figure 4) and that shows typical sequential patterns exist, which corresponds to each task performed by the worker.

For example, as a result of comparing feature parameters of "Walking" and "Moving panel" turned out that there are little variations of correlation of head and arm sensors of "Moving panel" and even the velocity of motion of arm sensor.

Moreover, since the motion of head and leg of the worker who performs "Moving panel" and "walking" is alike, the variation of correlation of head and leg sensors and the velocity of movement shows approximately the same patterns.

3.3 CALCULATION FOR THE NEURAL NETWORK OUTPUTS

The neural network is applied to the method of the recognition of tasks by feature parameters. Its model is designed in the three-layered Back-propagation network with the standard connections.

The recognition value, which shows the degree that suits each composition and operated from 0 to 1, was outputted using 12 feature parameters computed from 6-DOF data from the head sensor, the arm sensor, and the leg sensor as an input value of the neural network.

The feature parameters set for training neural network are collected by making the worker repeats tasks for the whole time units to estimate. The worker is equipped with the device of the monitoring system. The carried-out tasks were videotaped, and each of that feature parameters sets are named for every task. The inputs neural value for training the network is set to the feature parameters, and the outputs neural value is set to the name of tasks.

3.4 SETTING OF TIME UNIT FOR RECOGNITION

Several time units were set for different types of task because each task has own suitable time length for recognition. Since a time unit contains two or more tasks, the range of the time unit for calculating the feature parameters is longer and the probability of the error to an estimation value becomes high.

Moreover, since the amount of data which calculates the feature parameters decreases and the values are greatly influenced by each motion in tasks, when the range of the time unit for calculating the feature parameters is short.

Therefore, the authors set for several time units according to type of works for recognition. The minimum time unit is set for the task which requires minimum amount of time. The minimum range of the time unit is multiplied until it matches the maximum time of the task. The number of the time units from the maximum range to the minimum range is the sum of the total numbers of the time unit for recognition. This monitoring system, authors set the time range from "1.5 seconds" to "4.5 seconds". At "1.5 seconds", the minimum time range, 10 outputs in the range collected from sensors are used to calculate the feature parameters. "4.5 seconds" and "3 seconds" are set up as the other time units, too.

For other time units, the "3 seconds" and the "4.5 seconds" delayed by the minimum time units of 1.5 seconds from the start are also set. Since the start delay is for making the data of the feature parameters of the time units the optimal, no matter what time a task is started. (Figure 5)

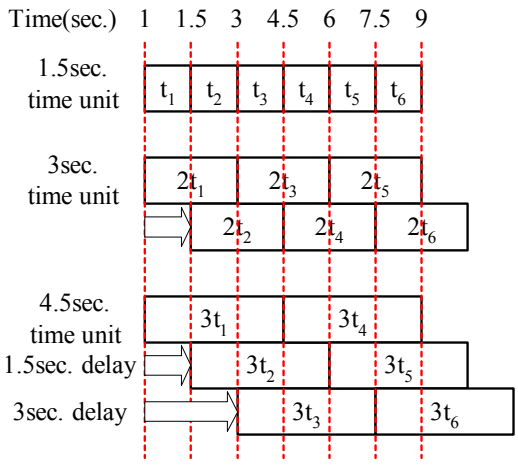

Figure 5. Setting of several time units for recognition

3.5 MONITORING OF THE SELECTED TASK IN EACH TIME UNIT

Six recognition values of the in each task are outputted from the outputs neural for the every time units. As a method of selecting the result of reliable monitoring from the six recognition values, the authors use the statistics value of the recognition values. The mean value of the recognition values is close to "1" and there are few deviations in each time unit becomes the measure which the task is selected as result of monitoring.

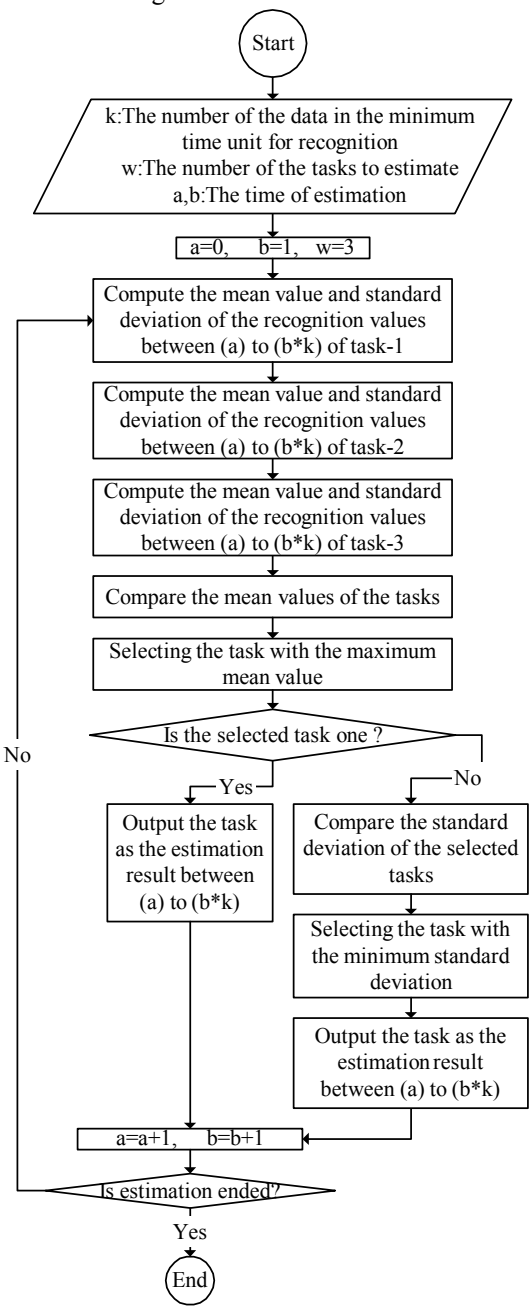

Figure 6. Task selecting flow

At the 1.5-second interval for selection of task, the mean values become the synthetic evaluation measure for estimation. Mean value is outputs neural for tasks in each time unit. The system selects the task as its estimating result, which has the maximum mean value.

When more than one maximum recognition values were found in the result, comparison of the mean values, the standard deviation for the mean value is adopted as evaluation value, and the estimation with minimum standard deviation is selected.

Estimation result of overall evaluation in the monitoring system is shown in Figure-6. First, recognition value for output neural in each time (between (a) to (b*k)) is extracted. Mean value and standard deviation in each component task are computed from the recognition values. Next, estimation is decided from comparison of mean values in each time. The task with the maximum of mean value becomes the selection. When selection cannot be made for two or more result having the same, maximum mean values, and the task with the minimum standard deviation becomes selected.

4. EXPERIMENTAL RESULTS

4.1 EVALUATION OF THE MONITORING SYSTEM

The authors conducted experiment to evaluate performance of the monitoring system. Feature parameters for "Moving Panel", "Drilling", "Walking" are collected through from a sample worker equipped with the prototype. Then authors went though training of neural network with feature parameter gathered, and established monitoring system for three types of task.

For developing system, Visual Basic by Microsoft was used and estimated result is displayed in each 4.5 seconds as designed and in real time. Mobile computer with Pentium(R) M 1Ghz was used for data analysis.

In experiment, the worker repeated the 3 tasks for 3 times, taking approximately ten minutes. Estimated result was collected at the time. The result was compared to actual data derived from videotape in 0.1 second interval and showed that 97.5% agreed. From the result, the system proved to function well. The possible causes of errors were seen at the end of task. Because two feature parameters are included in a 1.5 second time unit.

4.2 SUITABILITY OF THE MONITORING SYSTEM

Suitability of the monitoring system trained with a worker's feature parameters to other workers who have different physical and working characteristics are also examined. Five different workers used the same monitoring system used in previous experiment performed the same three tasks and data was collected for each. As shown in Table-3, workers are male with their stature vary from 163cm to 183cm.

Table 3. Body dimension of workers

Body Dimension	Worker				
	A	B	C	D	E
Stature(cm)	164	183	174	179	176
Reach(cm)	160	182	174	177	175
Crotch Height(cm)	70	92	83	85	84
Weight(kg)	60	70	64	60	70

As in Table-4, the system's estimation for these workers matched approximately 97% of actual tasks done.

Even the feature parameters were taken from the worker A, the rates of matched from other four workers were over 96%, proving that effect of workers physical characteristics and work pattern are remote and system functions effectively. Also feature parameter collected by monitoring system correctly figured out the characteristics of motion.

Table 4. Results of estimation

Worker	Index	Work			Total
		Moving Panel	Drilling	walking	
A	Time(sec.)	179.4	164.0	239.9	583.3
	Matched Time(sec.)	179.2	158.8	230.8	568.8
	Rate of Matched(%)	99.9	96.8	96.2	97.5
B	Time(sec.)	184.2	145.6	221.2	550.9
	Matched Time(sec.)	178.9	141.6	217.3	537.7
	Rate of Matched(%)	97.1	97.3	98.2	97.6
C	Time(sec.)	165.6	140.0	228.6	534.2
	Matched Time(sec.)	159.5	139.4	225.7	524.6
	Rate of Matched(%)	96.3	99.6	98.7	98.2
D	Time(sec.)	159.1	147.1	245.1	551.3
	Matched Time(sec.)	154.9	142.7	244.0	541.6
	Rate of Matched(%)	97.4	97.0	99.5	98.2
E	Time(sec.)	185.9	151.3	207.9	545.2
	Matched Time(sec.)	177.2	146.3	207.0	530.5
	Rate of Matched(%)	95.3	96.7	99.6	97.3

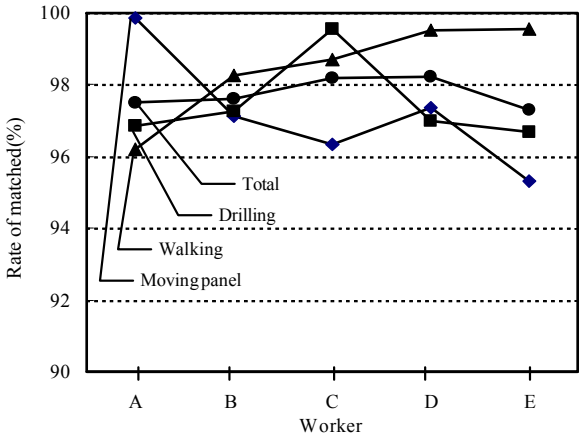

Figure 7. Rate of matched in each worker

Moreover, the relationship between percentage of each task for total working time and accuracy of the estimate is shown in Figure-8. As in figure, estimate of tasks which account more time such as "Walking" matches to actual work than the ones with less time, such as "Drilling" better, although the difference among them was within 4%. The system proved to be efficient for estimating various tasks which rate of time is at least 25%.

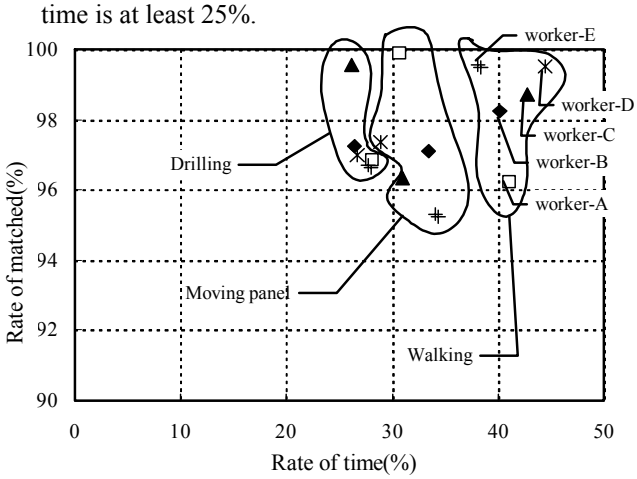

Figure 8. Relationship between rate of tasks for all working time and rate of matched

5. CONCLUSION

The authors developed monitoring system of data collection and utilization of 6-DOF motion sensor techniques in practical use.

Prototype was made based on the developed system and experiment was conducted. The result was compared to actual data and showed that 97.5% agreed. From the result, the system proved to function well. Moreover, the feature parameters were taken from a worker, the rates of matched from other four workers were over 96%. From the result, the system proved that effect of workers physical characteristics and work pattern are remote and system functions effectively.

This monitoring system is expected to be a tool of supervising workers at the site from the remote site office, by obtaining the information to current work progress and work performance of each worker with 6-DOF sensors.

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DIGITAL IMAGING IN ASSESSMENT OF CONSTRUCTION PROJECT PROGRESS

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Abstract: This paper presents a research effort designed to produce a digital imaging-based method to efficiently assess the level of construction project progress. Cameras are widely used to monitor and record various activities on a construction site. The images produced by the cameras can be processed with digital imaging techniques to help project participants better understand the status of the project. As the first step of this on-going research, this paper focuses on an image segmentation method designed to distinguish objects of interest, such as structural members on a construction site, from other objects in the image. The segmentation method combines an edge-based segmentation method with human knowledge of the construction scene represented by image morphological operations. A promising initial research result is also presented.

Keywords: Canny Edge, Digital Imaging, Morphological Transformations, Project Control.

1. INTRODUCTION

A construction project is a complex development that typically occurs in an outdoor environment and involves a variety of workers, a range of equipment, and diverse materials. To successfully complete a given project, numerous business decisions must be made by all levels of management; sound decisions are based on a well-developed project scope and project plan, and, most crucially, the ongoing reassessment of the changing and dynamic condition of the construction field. However, the complex, shifting nature of construction makes it extremely challenging to assess quickly and thoroughly the status of the construction field at any particular time. For example, it is a daunting task to track the progress made across a range of physical components during the construction of a facility, let alone verify the quality of that construction on a regular basis.

Image processing has been extensively and successfully used in many sub-areas of civil engineering, such as engineering document scanning, pavement distress assessment, site evaluation via satellite imagery, studies of crack propagation and microstructure in cement-based materials, and evaluation of soil fabric, etc [1]. It is a remarkably versatile tool that provides a means to augment existing methods of analysis and also opens up a large number of possibilities for significant advances in current civil engineering practices.

Although the geotechnical and transportation engineering sub-areas of civil engineering have taken the lead in applying image processing techniques to solve practical problems over the last ten years, the advancements in hardware and software developed for digital image processing and analysis provide promising opportunities in construction management and site investigation applications. Jayaram (1990) developed a conceptual system for digital image applications to produce as-built drawings [2]. Neto et al. [3] described a method of recognizing the presence of structure components in a digital picture taken at a construction site. Abeid developed a system called PHOTO-NET to compare the last picture taken at the end of the day with the last picture taken at the end of the previous day in order to automatically record and assess the progress of different activities [3].

Image processing has great advantages and shows potential to be a powerful tool since the resultant digitized, two-dimensional array format can be processed freely to provide information about the size, shape, and location of objects that are of interest to professionals in construction management. Thus, a digital imaging-based method is proposed in this paper as an effective means to enable the automated assessment of a construction project's progress, which may lead to advanced modes of project control. During the construction of the Natural Resources Engineering Facility of the University of Alberta in Edmonton, Canada, images obtained from digital cameras installed on site were used to monitor the project; these cameras enabled the timely tracking of activities performed on site in order to study the potential capabilities, effects and limitations of image processing in construction progress control.

The first step in this research is to differentiate the structural components and equipment from the background. However, it is not a simple task to

identify an object in a picture, especially if the picture depicts an open-field scene [3] in which the visual environment is complicated by elements such as lighting conditions, ambient facilities, weather, and other kinds of background visual interference. It is challenging to identify the various components of structures (columns, beams, and slabs, for example) and machines based on the images obtained on site. One of the most difficult problems in processing these construction-site images is that the significant amount of background visual interference is generated by various surface textures and colors, the shapes of materials and facilities, non-uniform illumination, weather conditions (i.e., snow or rain); other visibility elements also affect visual representations, such as the shooting angle and the position of the camera from which pictures are taken, or even the blockage of the line of sight.

The next important task is to accurately determine the locations or coordinates, and the size and shape parameters of the object. This task may involve multiple analyses of time-lapse images that are taken of the same object of interest at different times. Other key tasks in this research are to measure the progress made on a specific work item that is related to the identified structural components by means of time-lapse pictures and to distinguish the idle and/or working equipment on site based solely on the sequential pictures. Here in this paper, we only focus on the first task: segmenting the objects of interest (the structural components and equipment), and differentiating them from the background.

2. PROPOSED SEGMENTATION TECHNIQUES AND ALGORITHMS

To assess construction progress by means of image processing techniques that are available, the first and most challenging step is to recognize the objects of interest, various structural components (such as the concrete columns and steel beams), and equipment on site. A robust segmentation algorithm is required because the sizes, shapes and/or locations of these objects of interest in the images change frequently as the project advances and because of the heavy background noise. Morphological transformations are the basic techniques most used to extract and alter the structure of regions in an image; these are used extensively for quantitative analysis, observation of the geometry of regions, extraction of forms for modeling and identification purposes, and so forth [5]. Human knowledge of the construction scene, such as what a concrete column should look like, can be incorporated into the segmentation method by means of the image morphological transformations. For example, an image morphological filter can be implemented to choose only those objects with vertical box shapes such as columns and excluding all other objects with different shapes. The proposed segmentation method combines such morphological filters with a Canny Edge algorithm, an edge-based segmentation method, to produce more robust segmentation results.

2.1 Canny Edge Detector

The Canny operator [10] was designed to be an optimal edge detector for step edges corrupted by white noise; it exploits three performance criteria covering these elements: (1) good detection (no missing edges); (2) good localization (minimal distance between true and detected edge position); and (3) one response (minimum multiple responses to single edge). It takes a grayscale image as input and produces an image that shows the positions of tracked intensity discontinuities as output. The Canny operator works in a multi-stage process. First, the input image is smoothed by Gaussian convolution (convolve the image with a Gaussian of scale sigma). Then, a simple 2-D first derivative operator is applied to the smoothed image to highlight regions of the image with high first spatial derivatives. Edges give rise to ridges in the gradient magnitude image (compute gradient magnitude and direction). The algorithm then tracks along the top of these ridges and sets zero to all pixels that are not actually on the ridge top to produce a thin line in the output (a process known as *non-maximal suppression*). The tracking process exhibits hysteresis that is controlled by two thresholds: high threshold (T_H) and low threshold (T_L) where $T_H > T_L$. Tracking can only begin at a point on a ridge higher than T_H. Then, tracking continues in both directions out from that point until the height of the ridge falls below T_L (to eliminate spurious edges by hysteresis thresholding). This hysteresis helps to ensure that noisy edges are not broken up into multiple edge fragments.

Generally, the effect of the Canny operator is determined by three parameters: the width of the Gaussian mask used in the smoothing phase, and the upper and lower thresholds used by the tracker. Increasing the width of the Gaussian mask reduces the detector's sensitivity to noise at the expense of losing some of the finer detail in the image. The localization error in the detected edges also increases slightly as the Gaussian width is increased. Usually, the upper tracking threshold can be set quite high and the lower threshold quite low for good results. Setting the lower threshold too high will cause noisy edges to break up. Setting the upper threshold too low increases the number of spurious and undesirable edge fragments that appear in the output.

2.2 Proposed Approach in Research

The way to increase the possibility of delivering satisfactory segmentation results with high reliability and accuracy under the impact of heavy background

noise is to include as much useful information as possible. As mentioned before, Canny edge detector is entirely dependent on the image gradients though it is not as strongly related to shape of objects. Based on these technical characteristics of Canny edge detector, it is possible to obtain desirable segmentation results by incorporating other image processing techniques that involve human knowledge of the construction scene.

Figure 1 shows the flowchart of the proposed segmentation method. Initially, the original RGB (Red Green Blue) color images taken on site are loaded as input data, as shown in Figure 2 (a). To save unnecessary computing time, the regions of interest are cropped in an interactive manner using functions available in MATLAB software, and then the cropped RGB image is converted into a grayscale image. After that, this grayscale image is resized using the nearest neighbor interpolation method (Figure 2 (b)). Following this step, in order to correct nonuniform illumination of the resized grayscale image, grayscale morphological opening is applied to approximate the background illumination, as shown in Figure 2 (c). Here, the background illumination is estimated through grayscale morphological opening using a disk-shaped structuring element with a radius of 15 pixels. Next, the obtained background illumination image (Figure 2 (c)) is subtracted from the resized grayscale image of interest (Figure 2 (b)). In other words, each element of the background illumination image is arithmetically subtracted from the corresponding element of the resized grayscale image. This resultant output is an enhanced grayscale image that has uniform illumination, as can be seen in Figure 2 (d).

Then, image adjustment is conducted on the enhanced grayscale image to increase visibility of objects of interest because some of the original images taken out of doors and from a far distance are not very clear. Image adjustment increases the contrast of the image by mapping the intensity values of the input image to new values, as is shown in Figure 2 (e). After the grayscale image is adjusted, median filtering is performed to simultaneously reduce noise and preserve the edges of objects; this is done using a 10-by-3 vertically rectangular neighborhood. Each output pixel contains the median value in the 10-by-3 neighborhood around the corresponding pixel in the input image (Figure 2 (f)).

To make a further dimension of information accessible, Canny edges are subsequently detected, using a 5×5 Gaussian filter with high threshold value T_H and low threshold value T_L, as shown in Figure 2 (g). These two threshold values, T_H and T_L, are key parameters for segmenting the grayscale image into two regions: objects of interest and background. In order to get a desirable result, the optimal T_H and T_L are searched and captured in an interactive manner. The reason Canny method is applied here is that it uses two thresholds to detect strong and weak edges; it also includes the weak edges in the output only if they are connected to strong edges. The Canny method is therefore less likely than the other edge detection methods to be fooled by noise, and more likely to detect true edges.

After obtaining the desirable Canny edge binary image, the small gaps and interior holes are to be filled through the use of binary morphological closing and filling functions, successively. Morphological closing (a dilation followed by an erosion) is applied first, using a disk-shaped structure element with a radius of 5 pixels, so that the tiny gaps of the outlined Canny edges are closed, as can be seen in Figure 2 (h). Afterwards, a flood-fill operation is performed to fill holes in the Canny edge binary image, resulting in Figure 2 (i).

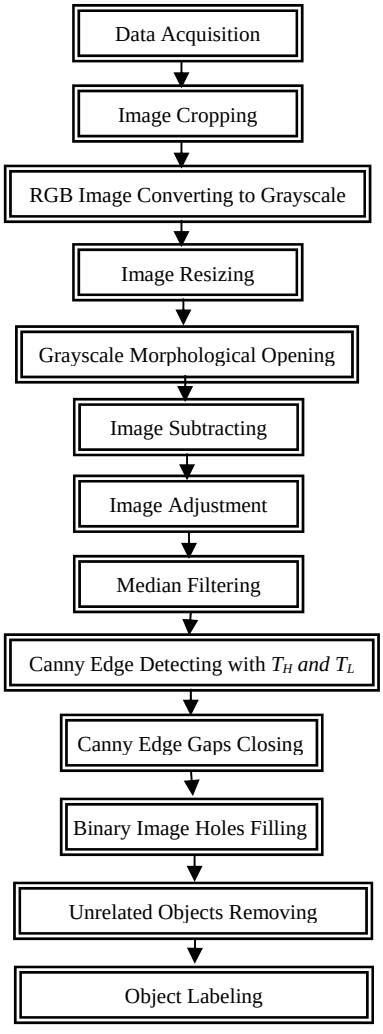
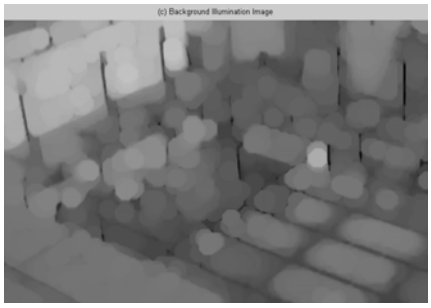


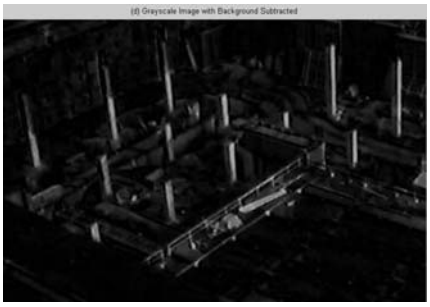
Figure 1. The Proposed Segmentation Method

(a) Original RGB Color Image

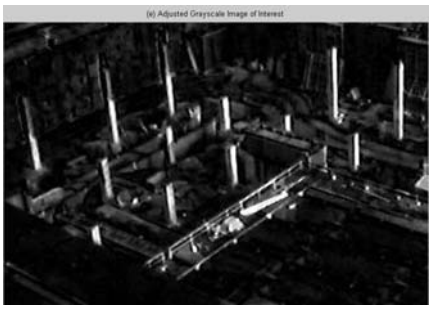
(b) Resized Grayscale Image of Interest



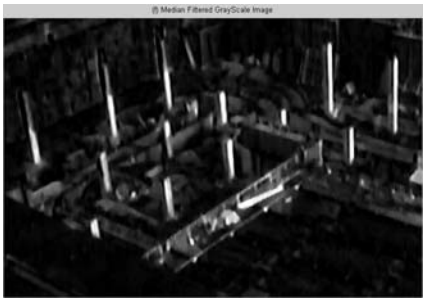
(c) Background Illumination Image



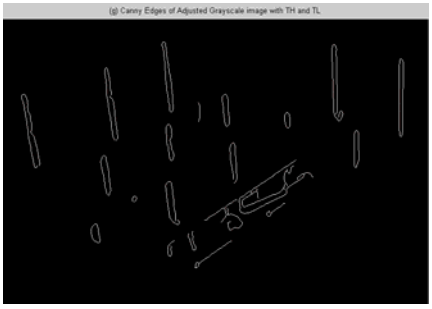
(d) Grayscale Image with Background Subtracted



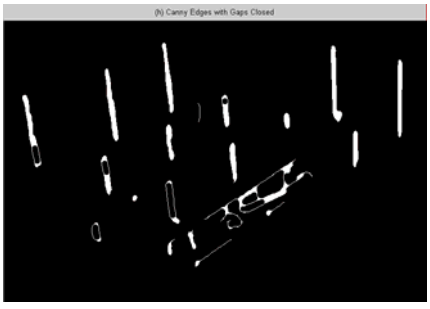
(e) Adjusted Grayscale Image



(f) Median Filtered Grayscale Image

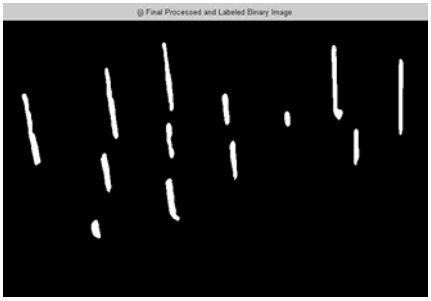


(g) Canny Edge Binary Image



(h) Canny Edge Binary Image with Gaps Closed

(i) Canny Edge Binary Image with Holes Filled



(j) Identified Regions of Interest

Figure 2. Images of Each Step of the Proposed Method

As the program processes, some morphology functions are used to remove pixels in the binary image that do not belong to the objects of interest. The basic steps include the following: (1) Determine the connected components; (2) Compute the area of each component; and (3) Remove small objects and huge objects that are significantly beyond the area of the objects of interest. Some objects connected to the border are also removed using a morphological filter designed to exclude all the objects that touch the image border.

At the end of the operation, the objects of interest in the Canny edge binary image are labeled, as can be seen in Figure 2 (j), and properties are measured for future analysis and application in progress control. In this step, the general procedure outlined in reference [6] is used to attach a unique label (identification number) to each separate region so that every region can be identified and processed individually.

Figure 2 shows a sequence of pictures that represent the steps outlined here in order to identify reinforced concrete columns on the building construction site as an example. A comparison between Figures 2 (b) and (j) indicates the promising result of the proposed segmentation method.

3. DISCUSSION OF RESULTS AND FUTURE WORK

The segmentation algorithm above successfully identified and segmented the objects of interest in the digital images taken on the construction site despite of the heavy background noise. After the objects of interest are separated, the parameters of each object in each time-lapse image can be obtained and analyzed for further studies. Since the shooting angle and position of the camera installed on site are fixed during a long period of time, major image processing parameters (for example threshold values T_H and T_L in Canny Edge detection) will not change sharply, and thus the data associated with objects of interest, such as the volume of concrete columns, can be automatically and efficiently obtained using the same image processing procedure aforementioned. This indicates a promising future for automatic construction progress control based on image processing techniques. To some extent, it breaks new ground to solve one of the most crucial and challenging problems in the area of construction automation.

However, further studies are needed before this method is applied successfully in more practical cases. After all, the edges detected by the algorithm discussed in this paper are not the true edges of the structural components; furthermore, some of the parameters of the 3D objects of interest are hard to obtain based solely on the 2D images. Therefore, neither the parameters of the structural components nor the productivity of each activity derived for the purpose of progress control is satisfactorily precise. To further enhance the performance of this methodology (to render it more reasonable and practical), the true edges of the objects of interest in each sample image are to be extracted and compared with the Canny edges to better investigate the relationships between them. With this in mind, advanced image processing techniques and human knowledge must be incorporated for feature extraction and comparison so that the results will be more desirable.

4. CONCLUSIONS

This article presents the outcome of an algorithm that can detect a structural component in an image taken of a construction site. The objective is to significantly enhance the performance of a image processing method and thus minimize the need to manually separate objects of interest in an image and, ultimately, to facilitate the dynamic progress control. The method for segmenting objects of interest is developed based on Canny Edge detector as it is incorporated with other morphological transformations. The Canny Edge detector initially outlines the objects of interest with optimal threshold values based on the enhanced grayscale image. This proposed method is effective as a means to segment structural components in digital images taken at the construction site. However, when many kinds of structural components need to be identified at the same time, or the structural components are too small (because the pictures are taken from a great distance), this algorithm needs further modification and therefore is still under development. Despite the problem mentioned above, the algorithm has produced very promising results and indicates remarkable opportunities for automatic progress control in the construction industry.

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Rapid Graphical Registration for 3D Complex Objects for Construction Workspace Automation

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ABSTRACT: Although considerable achievement has been made to the development of methods of extracting 3D geometrical information of objects from a scene, there are still major difficulties to visualize complex objects into descriptive CAD models. This paper introduces a new framework for rapid 3D modeling for complex planar objects which would enable automated material handling and semi-automated equipment control, and could significantly improve safety by enhancing operator's spatial perception of the workspace

KEYWORD: *construction automation, 3D, CAD, complex model, laser range finder*

1. INTRODUCTION

Using automated or semi-automated equipment on a construction site requires rapid recognition and accurate measurement of objects in the workspace so that timely on-site decisions can be made. Graphic workspace modeling can help to optimize these automated and semi-automated equipment control, significantly improve safety, and enhance a remote operator's spatial perception of the workspace. Current methods for extracting geometrical data from construction sites are comprehensive local area modeling based on fusion of dense point clouds, which is impractical and unnecessary in practice in the near future [1][2]. By strategically incorporating human assistance, which can simplify and accelerate geometrical data acquisition of real-world objects considerably, the ability to extract models of real world objects in a construction workspace for equipment operations from only a limited number of scanned points is a significant advantage of this approach over full range scanning methods that require computationally intensive range data processing.

Recent research conducted from the University of Texas at Austin has successfully demonstrated rapid registration of 3D primitive objects to workspace based on measured scattered point data [4]. However, the research was confined to the registration for selected simple primitive models which require a certain number of parameters to determine the boundary of objects such as a cylinder and a cuboid. Since more complex objects can be easily found than primitive objects in construction workspace, there has been a strong need to develop algorithms and more efficient data measurement processes to rapidly register 3D complex objects to the graphic work environment. Due to the complexity involved to measure all required parameters to generate complex models, which is unacceptable in the midst of the on-going construction operation, there have been few efforts made to solve this problem.

This paper presented an on-going research at the University of Wisconsin at Platteville (UWP) and demonstrates a framework and a schematic process of algorithm development for graphical regeneration of real-time geometric information of complex planar objects with respect to their location and orientation.

2. MODEL-BASED RAPID REGISTRATION

The current approach to workspace modeling includes human-assisted sparse-points based local area sensing and fitting matching process with pre-stored models.

2.1. Human-assisted sparse- points based local area sensing

Since most target objects are known and man-made, they can be described as a generic set of parametrically defined graphical objects in a computer database [2]. For the rapid registration, the geometric information of complex objects needs to be graphically generated and stored in a computer database as pre-stored CAD models. Such a library of pre-stored models (related to facility design elements), with manual guidance, can provide graphic representations of forms that can be matched and fitted to sensed data from 3D position sensors deployed in the work environment.

Earlier version of the algorithm was programmed to directly measure vertices from the object. However, it was difficult and time consuming for the operator to measure exact vertices or edges from an object

with a single-axis laser, which showed some inconsistent results. Figure 1 shows a reflection problem when a laser focuses on a vertex on the target object. The laser may read the behind reflected dot measurement.

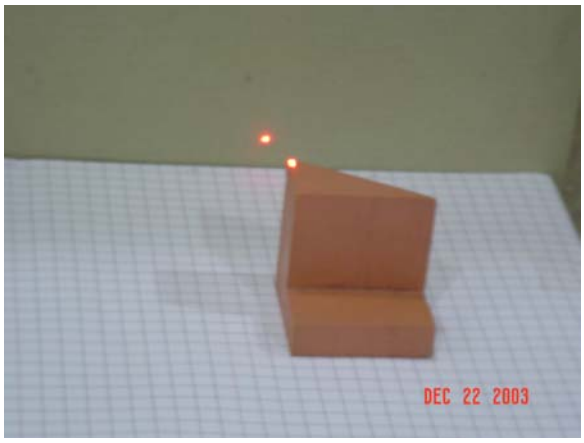

Figure 1. Reflection error showing a laser beam splits into two dots

For a more efficient and better user friendly measurement process, the algorithm needed to minimize the operator's possible position measuring errors. Therefore, the current algorithm which is currently being developed allows the operator to measure scattered random points from any visible surfaces of the object. This approach will provide a faster and more accurate position data measurement process rather than directly measuring vertices or edges from the objects.

For a fitting and matching process, a minimum of certain number of scanned points measured from surfaces of objects are required. In this approach, a minimum of three vertices are required for fitting and matching process for objects which have planar surfaces. To generate three vertices, well-selected five planes should be generated. To generate a plane, a minimum of noncollinear three points on the surface are required. Therefore, a minimum of total fifteen points (=5 surfaces x 3 points) should be measured using a single-axis laser range finder with manual guidance.

Figure 2. Sparse points sensing by a single-axis laser range finder.

The current three degree-of-freedom (DOF) laser system (including a laser beam), however, measures points from limited visible surfaces due to its lack of DOFs (Figure 2). For example, it is untenable to have five surfaces of box viewed from one location. To obtain required point range data from five different surfaces, therefore, the laser range finder should move around the object. This problem can be solved when the laser system is mounted on a robot arm like an eye-on-hand configuration (see Figure 3). Papanikolopoulus [5] describe that the robot-mounted camera (eye-on-hand configuration) can eliminate the need for accurate calibration and assumptions about the workspace.

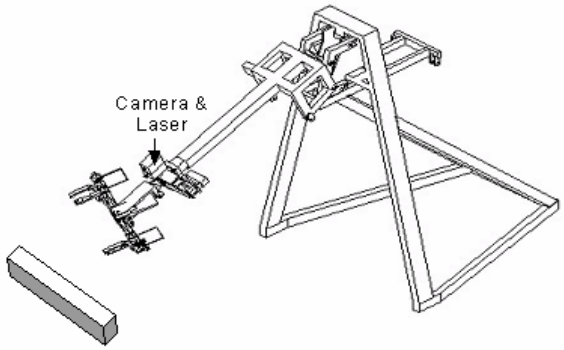

Figure 3. The Laser and Camera System on the UT Large Scale Manipulator.

2.2. Fitting and Matching Process

For a fitting and matching process for a planar complex object, there are mainly two algorithm development steps as follows:

2.1.1. Determining vertices

Once the sets of three points data are received, planes are determined by the equation of plane, $ax+by+cz+d=0$. Two planes always intersect in a line as long as they are not parallel. The intersection of three planes can be determined by solving the set of linear equations with Cramer's rule [3].

$$a_1x+b_1y+c_1z+d_1=0 \text{ ------- } P_1$$
$$a_2x+b_2y+c_2z+d_2=0 \text{ ------- P2}$$
$$a_3x+b_3y+c_3z+d_3=0 \text{ ------- P3}$$

By solving each set of three plane equations, four vertices of the object are determined (Figure 4):

1^{st} Vertex from $P_1P_2P_3$
2^{nd} Vertex from $P_2P_3P_4$
3^{rd} Vertex from $P_3P_4P_5$
4^{th} Vertex from $P_1P_3P_5$

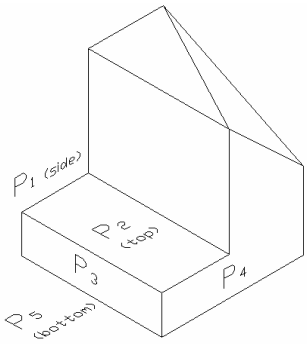

Figure 4. Example of five planes selection

2.1.2. Fitting and matching a pre-stored model to the vertices

As a second major step, the algorithm moves and rotates the pre-stored model to the corresponding vertices obtained from the previous step. First, a selected vertex on a model is moved to one of measured positions. Second, a distance between first and second measured points is calculated. Third, the program searches a second point from the model which has the same distance calculated from the measured first two vertices. These three steps continue until the program matches the corresponding two points. Fourth, once the program found the two points on the model, an arbitrary axis is generated to rotate the second point on the model to the measured second vertex with certain angle. The angle can be obtained by solving concatenated inverse transformation matrices. Finally, the program uses the first two fitted and matched points as an axis to rotate a third point on the model to the measured third vertex. Another angle needs to be solved from the same inverse transformation matrices. However, sometimes three points may induce a directional confusion in the boundary. An additional point can prevent this problem (Figure 5).

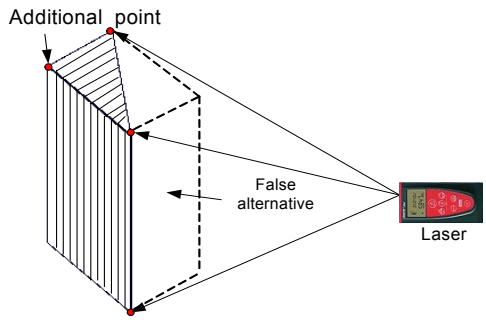

Figure 5.

3. ERROR ADJUSTMENT

In the field of automation and robotics, sensors have long been used in the laboratory under controlled conditions. However, sensing often fails due to unanticipated problems relating to the sensor, the robot, the integration of their respective systems, and the environment [5]. For a single axis laser range sensor, the sensing errors depend on distance to measured points, laser power, target reflectivity, angle of incidence, and laser beam focus.

In the fitting and matching process, there are two places requiring error adjustment due to the aforementioned error sources. First, the measured scattered points on each surface should be modified to generate ideal surfaces. After grouping points for each surface, a statistical approach will be used to reposition erroneous points to each ideal surface. Second, certain tolerance should be allowed when the points on the model are fitted to the measured corresponding vertices of the object.

Compared to the method which creates or draws models from measured and calculated boundary data, however, this model-based fitting and matching method yields higher accuracy. Although position and orientation error problems still remain due to the nature of sensing error sources as mentioned before, this method does not distort nor deform models in the fitting and matching process because the models are designed and stored to the library in exact dimensions.

4. Simple demonstration of fitting and matching process

A simple test for rapid registration was conducted for the object which had eight planar surfaces (see Figure 4). Since the object is sitting on the horizontal surface as a known base surface (height, z = constant), data were collected from only four surfaces instead of five. Figure 5 shows the fitting and matching process for this object. Actual processing time takes less than a second.

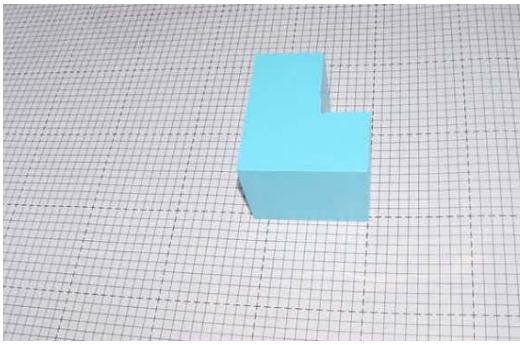

Figure 4. An object with 8 planar surfaces on a grid sheet

Figure 6 illustrates a framework for the overall rapid graphical registration process which is being developed.

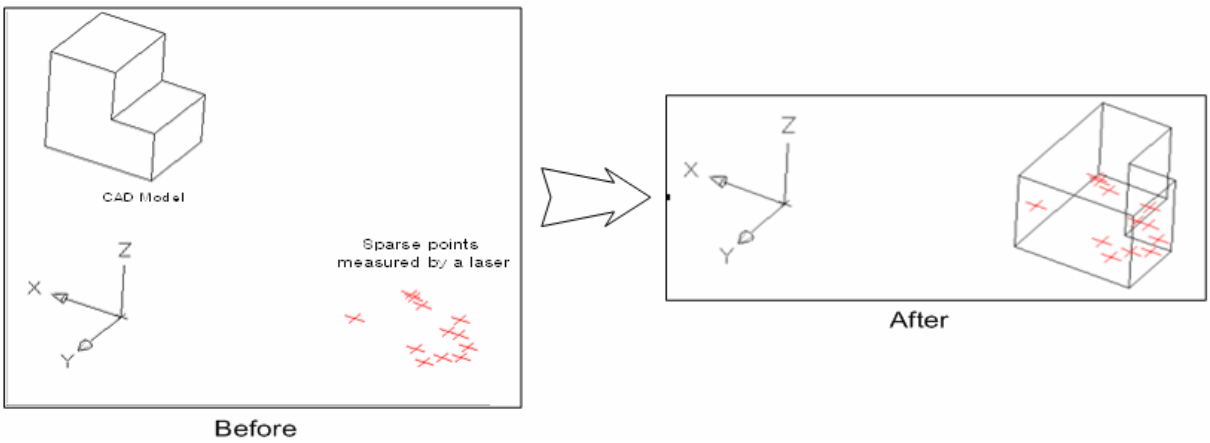

Figure 5. Fitting and matching demonstration

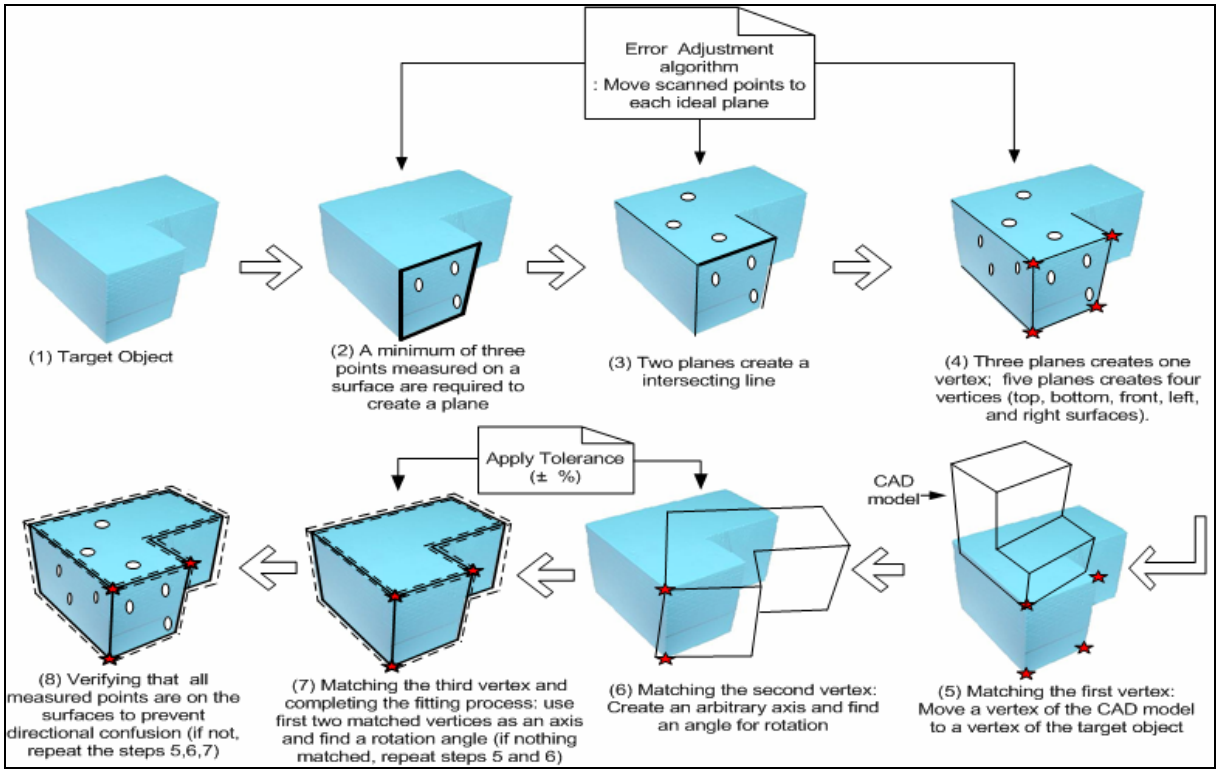

Figure 6. A framework for rapid graphical registration process

5. Current and up-coming research tasks

Current tasks this research are conducting include developing a measurement error adjusting algorithm and developing a fitting and matching algorithm for curved surfaces including a cone, a tiered cylinder, a pipe elbow, a sphere, and combination of curved and planar objects. As a final stage of this research, test beds with one of available robots at UW Platteville lab (see Figure 7) for material handling and welding will be designed for the final performance evaluation and improvement of this method for practical use in the construction automation industry.

Figure 7. Miller 6 DOF welding robot at UWP.

6. CONCLUSIONS

Recent research indicates that the ability to match and fit pre-stored models with real world objects in construction workplace is a significant advantage of workplace automation. This paper presented an on-going research at the UW Platteville which introduced efficient methods for rapid registration of 3D complex planar objects to the graphic work environment.

The rapid approach will be useful in construction in order to optimize automated equipment tasks and to significantly improve safety and a remote operator's spatial perception of the workspace.

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AS-BUILT POINT CLOUD REVIEW OF A CEILING PLUMBING SYSTEM

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Abstract: This research used a 3D scanner to retrieve the geometric information of finished pipe layout inside ceiling space and used the 3D point clouds to facilitate follow-up building management. The presence of as-built pipes enables the measurement of relative locations between various pipes, pipes and slabs, or pipes and walls. This allows the building contractor to determine if plumbing space should be increased with toleration according to the layout or possible maintenance of pipes and the passing route in the future.

Keywords: 3D scanner, point cloud, plumbing, as-built shop drawings, facility management

1. INTRODUCTION

In building plumbing shop drawings, most require the location of the beginning and the end sections. The route and location of the plumbing always change during work on site (Mokhtar et al. 1998). Building plumbing acts as a resource supplier. It not only supplies base requirements, like a drainage system, power and electric system, HVAC system, and gas system, but also it bears Internet pipes or other special pipes for special needs. Everyone is satisfied if the building can use them normally. Therefore, in the building construction process, the building requirements of the future are considered during plumbing configuration. The configuration requirements consider a user's need for determining location and the pipe openings for future use. In the beginning of planning and design, the architect discusses with users about configuration types and produces design to fit their behavior. During actual construction, how pipes location will match with user requirements is considered.

The location and condition will lead to measured difficultly in building plumbing configuration, and influence the work of record. Building are used for a long time, it is possible that the users will change or its purpose, requirements, and equipment renewal needs so that they do not conform to new user requirements. It must change or renew plumbing to satisfy new requirements. However, required pipe equipment is numerous, and the routes are always different with spatial requirements that are not the same. Therefore, when it needs to renew or maintain plumbing, it must investigate the location and function of present pipes for important plan reference information. When buildings are old, it more difficult to control pipes location and routes. Many pipes are configured in the ceiling, when ones needs to refit the pipes must understand the spatial relationship with other pipes so it can determine how to configure other pipes. In the past, even though there were-built drawings of plumbing, the locations were not correct, which led to deficient configuration plans. The result was that the ceiling plumbing produced much difficulty for interior measurement. This presents a great obstruction to new pipe configuration. Therefore many plumbing configurations using clear pipes or in accordance with site conditions, cannot plan effectively in advance.

Since the record on site cannot adequately show the location of pipes, the result is that as-built drawings are different from the real situation. The long-range 3D scanner satisfies this recording requirement. Because the point cloud has three-dimension characteristics, it can, via point cloud, display completely to the relationship of the pipes that is not limited to traditional two-dimension diagram information.

This research used a 3D scanner to scan the plumbing in a building's ceiling to record the plumbing's real location. When ceiling was being installed, we scanned the ceiling twice, before and after the installation, to record the ceiling location in the building, and to register two different scans, and allow the pipes real location is correctly display. When we confirmed the interior pipe location and surplus space in the ceiling, the plumbing designer can use these spaces to plan and configure plumbing, and create reasonable configuration routes. It will not influence the original function of the building, and maintain the original building shape.

2. APPLICATION OF THE 3D SCANNER ON BUILDING CONSTRUCTION

The usual method of building construction monitoring used photos and video along with text.

However, using the limited two-dimension image display, photo and video only for reference to construction process record cannot be used as a reference for future building maintenance issues. The major reason is that the two-dimension image could be easily be interpreted incorrectly. Recently, many researchers demonstrates how to record real environments in 3D mode, such as using photogrammetry to record construction sites or real building shapes, by creating a 3D model from photo images and record the relation of a real building model and environment (Powers 1996; Heuvel 1998; Dorffner and Forkert 1998).

The 3D laser scanner gives a new choice for traditional measurement or photogrammetry. It uses a laser to produce 3D point cloud information in real time. This research used a 3D scanner (Cyrax 2500) to do long-range scans. It can produce a 999*999 matrix maximum. Its scan tolerance is about 2mm at 50 meters. The point density can be regulated by detail requirements. It can register used targets of multiple scans by Cyclone software. There is no limit for the volume and range of a target object (Shih 2002).

Point cloud can display the shape of a large-size building or scanned body, so it is useful for recording historic buildings or important landmarks such as a large sculpture (Rocchini et al. 2001), urban environment (Zhao and Shibasaki 2001), or analyze construction component problems with a RP machine (Shih and Wang 2002).

This research used a 3D scanner to record building plumbing to produce a point cloud readout. It not only can display a three-dimensional record of the pipes, but also can determine the relation between the pipes and ceiling when the ceiling was installed. It used Cyclone to combine different time point cloud results into a single file. This allows us to understand the status of the ceiling and plumbing by point cloud. Cyclone was used to build a 3D model of the ceiling and plumbing and to install the file into general 3D drawing software to design and plan plumbing configuration. It can use this three-dimensional space to simulate follow-up plumbing design.

3. THE WAY TO RENEW PLUMBING IN AN OLD BUILDING

After a building is finished, times accumulate and the way that it is used constantly changes. For example, equipment can be changed or there is a need to work with the plumbing. The building space follow user's requirement as they change, therefore many spaces and plumbing are not in the original design concept. In order to satisfy new user requirements, it must face space changes to change or regulate plumbing equipment. Now, most buildings are easy to maintains since they used clear pipes during construction. Beside the shaft, most plumbing is configured in the ceiling. So many pipes use a ceiling's interior space. However, a building has so many types and number of pipes, the architect could not coordinate everything before construction. So many plumbing configurations need to coordinate and configure with construction site conditions (Ambrose 1992). Most shop drawings only display the beginning and the end of the plumbing, the actual routes and location are improvised on-site during construction by the workers. On the construction site, there is always a need to change the design of the plumbing configuration (Ai-Momani 2000; Cox et al. 1999). However, most changes in location are not recorded. This means that no one can efficiently maintain the plumbing in the future.

In plumbing, if you wish to increase the number of pipes it is very difficult since the plumbers do not record effectively the location and information of the pipes. This causes difficulties for future maintenance needs. This major reason could be spatial user change plumbing for need by himself. A plumber will not be able to coordinate with building management since no one can understand the configuration of the pipes. This causes much difficulty for management and maintenance personnel. So, if the construction company can record effectively location and information of plumbing, it will let management work conveniently.

When architectural firm plans and designs building plumbing, a technician is assigned to do the actual plumbing design. However, every technician makes the plans independently, which allows pipes conflict to with each other, and influence improvised plumbing configuration on site. Almost all architects face the plumbing coordination problems before construction, and then on the construction site, when there are plumbing conflicts that need to be corrected on site. Although it does not influence use and function, it influences the difference with the original shop drawings. As-built drawings cannot correct for the new plumbing routes, therefore actual pipes locations cannot be confirmed. If the building needs to change its plumbing scheme, it cannot confirm the location of pipes in relation with ceiling surplus space, and just develop another space to configure besides the building. The function is solved, but it will continue to destroy the building surface and normal use behavior.

Ceilings can hide many pipes and large-scale buildings have many types of pipes, whose management is difficult. So most use clear pipes during construction. This increases interior space beauty, ceilings are used to segment plumbing to offer a better aesthetics. Since the ceiling is isolated, it will ignore many hidden problems. Beside some dirt and toys, it is a difficult place to maintain the plumbing. In the past, to fulfill temporary requirements to configure some pipes, building management would hire workers to solve the problem function satisfactorily. But for the plumbing manager, he cannot adequately control pipe changes

and prevent possible maintenance problems. In the past, plumbing shop drawings could not offer correct information to building managers, when they needed to renew or maintain the pipes, so they usually did not know what to do. The only way learn about the plumbing is to begin from the starting point and set up new pipes. This maybe is a quick solution to settle the requirement, but it is not a permanent answer. If plumbing continues to increase, it not only makes building resource bear greater loads, resource management efficiency degrades. It only let plumbing manage transparently, to understand where pipes location and surplus space are located. Pipe maintenance can develop its main action, to help managers to work economically and effectively.

4. USE 3D SCANNER TO RECORD BUILDING PLUMBING

This research used a 3D scanner to scan finished plumbing configuration and ceiling installation, record pipes status and corresponding ceiling locations at that time. The scanned object is an L-shape steel building that is twelve stories above ground and three stories below. There are discourse halls, classrooms, and research rooms. Since the plumbing is complicated in this building, and we had limited time and manpower, the researchers chose to focus on the toilet ceiling and HVAC duct of discourse to scan. The interior must consider scan range, the scanner cannot use one scan to record, it must register multiple scans to be complete (see Figure 1.). Therefore, it must consider the location of the scanner and targets for different scan point clouds to register. Moreover, we want to understand the location of the ceiling in the building by scanning the ceiling when the ceiling was installed. We used Cyclone software to register two different time point clouds, for easy observation of the mutual relationships between the pipes and ceiling.

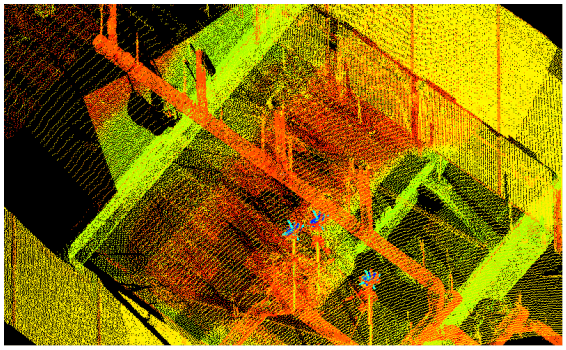

Figure 1. Point cloud of toilet plumbing.

After the 3D scanner records the building's plumbing, it can display plumbing location with point cloud in three-dimensions. Cyclone allows us to rotate, zoom in, zoom out, and define slices, as well as watch and measure the relative location of the pipes in spatial point cloud (see Figure 2.). This allows us to understand quickly the relationship between pipes and ceiling, and via point cloud to control pipes real location and past routes. This information is very important for plumbing maintenance or design. They can use this information to search pipes and plan renewal plumbing projects.

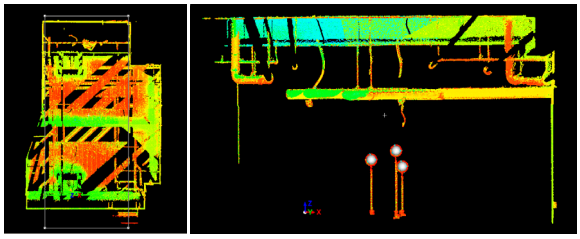

Figure 2. Define slice or fence to watch and measure pipes relative location, left is plan, and right is section of fence.

During the actual building construction, its internal and external scans will follow changes over time. So every time point a scan is recorded is from real information on the site. However, for cases with uninfluenced construction procedures and interference by a construction worker, this study always scans a finished area, such as when toilet-plumbing configuration finished. This team had four people scan a finished area, and record complete plumbing information. When the area ceiling was finished, a wall and slab were done at the same time. We must scan again to record the toilet status, inspect the difference between different times, and register different times point cloud to combine them and determine a basis of the ceiling's internal space.

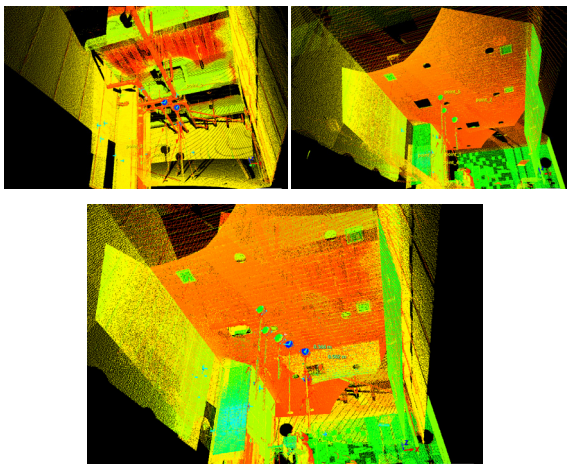

Figure 3. Used different time of toilet scanworlds to register. Top left is first time status, top right is second time to scan, and bottom is registering both scanworlds.

In general, the scan should be done at the same time, because the targets had been set up on site, the location of targets do not change, it will use Cyclone for registering. In different times, the two point cloud scanworlds change due to changes over time to the interior, like increase ceiling, wall finished, and slab

fixed up. Almost everything is covered with the first time scan. So it is hard to find suitable targets to register on different times. This research uses software to calculate ability and determine targets on different time point cloud to set up in the same places which could be different due to the thickness of finished, and some partial pipes from ceiling overhaul openings. It can reluctantly point cloud register. It has some inaccuracy, but the value of inaccuracy is in unacceptable range (see Figure 3.).

5. TO DETERMINE THREE-DIMENSION SPATIAL RELATION IN THE CEILING

After the different time periods are registered and combined with point cloud, Cyclone can observe the relation between the pipes and environment in ceiling. It can watch clearly the location of pipes and corresponding relation between the slab, ceiling, wall, or other pipes (see Figure 4.). So it can measure quickly from point cloud to understand the real location and keep it as well as decrease many possible errors.

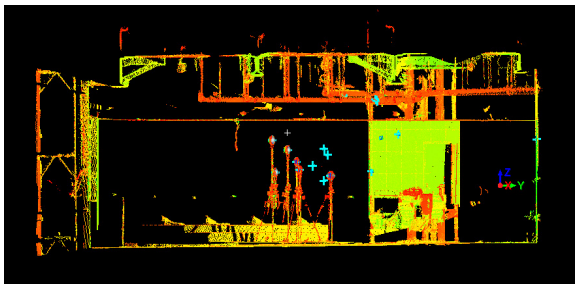

Figure 4. Section of the location of pipes and corresponding relation between the slab, ceiling, wall, and other pipes.

In the past, if someone wanted to measure the spaces in the ceiling it was difficult enough that one almost could not investigate and measure ceiling interiors. This research used scan operations from different times to record the location of the pipes and ceiling. It also used a register to check and inspect ceiling interior spatial requirements. Point cloud format (.imp) was used to transform the data into CAD software acceptable format (.dxf)(see Figure 5.). Next, it proceeds to reveal the environment it is operating in so it can easily find surplus useful space and capacity to offer the plumbing designer.
This study finds much spatial information that can be configured beneficially and possibly create plumbing arrangements that facilitate pipes information control. There is no longer a need to configure ugly pipes outside of a building, but also perform the most appropriate work in the ceiling interior by reaching the purpose of spatial application and the requirements of plumbing management.

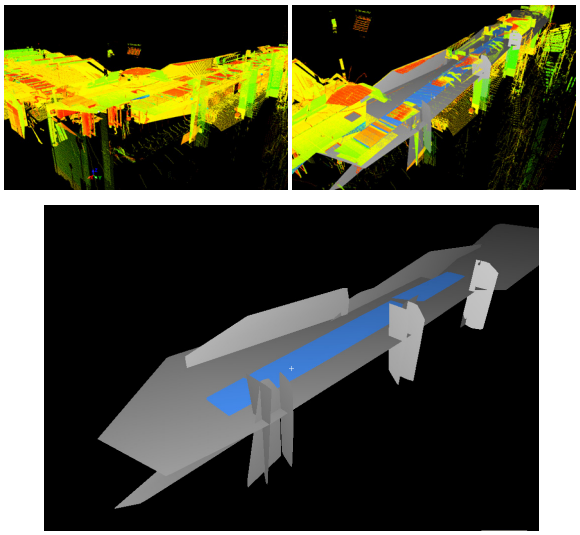

Figure 5. Point cloud transformed into .dxf format to CAD to describe the space in the ceiling. Top left is original point cloud, top right is segment to patch on point cloud; bottom is transformed to .dxf format.

Laser light is used to calculate the real location of the scanned shape, so many backlighted areas cannot display point cloud information. Although it can use targets and multi-scans to decrease vision dead space, the pipes configure better in interior space. It is difficult to scan from top to down, so it will produce some dead spaces. On construction sites, every day has different schedules, so the construction site's contents vary from minute to minute. It is hard to find permanent targets in the construction site, when registering point clouds, one needs to look for landmarks from previous visits and some luck in calculation process. In the final analysis, follow-up point cloud information that has not any been calculated with previous point cloud scans is difficult to register.

6. CONCLUSIONS

This research used different times to record construction in order to discover if it can perform effective point cloud scans in spatial real location, and register ceiling relation status. This information allows the building plumbing or plumbing maintainer to have important referable information regarding spatial changes to reduce equipment or pipes. It can help users understand and determine the location of present plumbing and analyze possible configuration locations in the future. The building interior plumbing arrangement has to be systematic and orderly and not influence follow-up management work.
Since this scanned building is behind schedule, many workers come and go during the construction process, which negatively affects schedule control that will influence scan quality and results. This study almost did not interfere with the workers during the scanning process. But there were still some effect on

the scan rate of progress and contents of the scan.
The area between the plumbing and ceiling space is hard to control in general. This research focused on this problem to offer a method to measure the relationship between the pipes and space in the ceiling. We believe that it can help plumbing designers work in new directions and refer to a basis to plan and make designs with less pipes and less maintenance worries. It will also help the building plumbing manager to manage plumbing and keep the building appearance neat.

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DEVELOPMENT OF LOCATION-BASED INDOOR FACILITIES MANAGEMENT SYSTEM

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Abstract: Many facilities management systems depend on location information for identifying facilities of interest. However, obtaining location information in a large open space is not sometimes easy due to lack of landmarks. Although Global Positioning System (GPS) is well known for its ability to provide accurate positioning when used outdoor, it was seldom intended for indoor environment because the satellite signal tends to be week or deflected inside the building. Several indoor location identification systems therefore have been developed. This paper presents how a prototype location-based indoor facilities management system was developed and tested using the indoor location system.

Keywords: Facilities Management, Indoor Location System.

1 INTRODUCTION

Location of facilities is one of the key elements in facilities management. Many facilities management systems depend on room numbers or signboards for identifying location of facilities. However, location of facilities in a huge open space such as the lobby of an international airport terminal may not be easily identified due to lack of landmarks to be utilized.

Global Positioning System (GPS), which is a technology designed to identify the user's location in the globe utilizing electronic waves transmitted from artificial satellites, has a great potential in outdoor facilities managements. However, it may not be effectively utilized for indoor facilities managements because the strength of the GPS signal tends to be reduced significantly inside the building by the external walls and roof.

Recently, several indoor user location identification systems have emerged. Most of these systems are utilizing GPS technology to identify the user's location. The transmitter sends signals of its location using electronic wave and/or ultrasonic wave. Signals transmitted to the receiver are then analyzed by trigonometric function to identify the user's location. Some indoor location identification systems are designed for mobile devices such as Pocket PC. The process of manipulating location information of indoor facilities is therefore expected to be improved if the mobile-based indoor location identification system is applied for indoor facilities management.

2 MOBILE COMPUTING

Mobile computing is expected to improve facilities management in field by reducing laborious and redundant work. A facilities management system loaded on a mobile device would enable facilities managers acquire inspection data and update them in field without going back and forth to the office. These data would be synchronized with the main database later whey they come back to the office. Facilities managers therefore would avoid the process of entering inspection data in the main facilities management system, which often causes data duplication or omission.

The Texas department of Mental Health and Mental Retardation (TDMHMR) recently decided to use mobile devices to improve its facility management system. Instead of paper work orders, the TDMHMR use a Personal Data Assistant (PDA) to assign and track work orders. Through this process, work orders are downloaded to the technician's PDA and can be filtered and resorted by location, priority, and work type. When workers arrive at the site, they can cross check the procedure checklist stored in the PDA. Once they've completed the tasks, they can record the time spent and materials used in each task before moving on to the next assignment. At their convenience, workers can upload and synchronize the PDA with the database, closing completed work orders and recording time and materials automatically [1].

Some mobile devices, such as Intermec 5020 and Symbol MC9000-G, are even armed with bar code scanners. Facilities managers can acquire information on any items simply by scanning their bar codes. Hence, they can easily add/edit/delete related information pertaining to that item on-the-spot without the usual hassles of manual data entry and paper work routines. Both Intermec 5020 and Symbol MC9000-G use Microsoft Windows CE as the operating system and include the standard-based wireless network (802.11b or Bluetooth) that enables real-time communication [2].

At Northwestern Memorial Hospital (NMH), facilities management department uses PDA to manipulate Life Safety Systems, which have over 2,000 fire and smoke dampers scattered throughout its main facility unit. The PDA-based Life Safety Systems Management (LSM) is comprised of a PDA, a bar code reader, LSM software, and a Microsoft Access database on a host desktop PC. The process begins with a field survey to locate and barcode the desired devices. Inspectors then enter all the relevant information and results from the inspection of each device into the PDA. After the completion of the survey, data is synchronized with a host PC and linked to the facility's CAD files. The system's web-based front end allows authorized users to access the location and maintenance history of the devices via the Internet. With this new technology, NMH staffs are no longer burdened by tedious tasks of storing and filing heaps of outdated, hard copy inspection reports but can now easily access and update them via the Internet [3].

At West Coast Airport, Tablet PCs have been utilized mainly for security purposes. Autodesk, Inc. set up a pilot project to extend its security application, Homeland Security Initiative. The Autodesk Homeland Security Initiative is an application that delivers a suite of design and mapping applications that give first responders and emergency personnel quick access to data that are crucial to the safeguarding of infrastructure, enhancement of public safety, and management of emergencies. With the capabilities of the Tablet PC, emergency responders can access critical information on scene using live spatial data, maps, aerial imagery, and situation planning. Among the units and departments that participated in the pilot test included Airfield Operations, Terminal Operations, IT, Project Management, Facility Management, Environmental, and the Airport Managers Office. The pilot test was proven a success. Tablet PCs offered the management the flexibility to react with greater speed, efficiency, and accuracy, especially at times when public safety is at stake [4].

Computerized Maintenance Management Systems (CMMS) loaded on a mobile device enables facilities managers open or close work orders while conducting building inspection. Information on work orders is transferred to the central database via a wireless network that allows other managers or technicians to access up-to-minute information. Moreover, CMMS is connected to a web-based information system and allows customers to request maintenance services via a web browser [5].

Wearable computer is another mobile device that can be applied for facilities management. Mobile Inspection Assistance (MIA) is a good example. It consists of a portable pen-based computer that can be worn on the hip or chest; a Head Mounted Display (HMD) with audio device that allows inspectors to record exactly what they see; and a durable battery set that powers the system [6]. The software application of this MIA system usually consists of five functions: a graphic user interface that presents the previous inspection reports, current inspection form, collection of sketch templates, and photo album; a speech recognition tool that allows inspectors to invoke commands via speech; a database for storing information; a tool for sketching; and a tool for viewing/editing photos [7].

3 LOCATION INFORMATION

Often times, location information is critical for facilities management or construction management. Global Positioning System (GPS), which calculates the position in the globe using satellite signals, has been actively utilized to obtain outdoor location information.

When Mt. Fugen volcano in Japan erupted in 1994, two canals were constructed to guide lava flows into near sea. Since the construction was carried under the constant threat of lava flows, unmanned backhoes, bulldozers, and dump trucks were employed at the job site and were operated by a remote controller from a safe distance. Operators monitored several screens showing images from cameras on the vehicles or at the job site. However, the lack of true visual and depth perception increased the collisions between equipment involved in the operation. In order to solve this problem, a system to sense and warn vehicles of impending collisions was developed using Global Positioning System (GPS). The collision detection system calculated the distance from the potential collision point to each vehicle location using location information obtained from GPS [8].

GPS is sometime applied to monitor deformation of super structures. The KOMTAR building, the tallest building in Malaysia, is equipped with GPS-based stations to monitor the building's movement for preventive safety assessments. These monitoring stations record basic coordinates of reference points at regular time intervals and analyze the stability of the building. With this GPS technology, the building's supervisor could have up-to-minute information of the deformation of the structure and could rescue many lives from the disaster [9].

After the terrorist attack on September 11, 2001, New York City's Department of Design and Construction (DDC) led the recovery effort for the World Trade Center disaster, the overwhelming task of removing more than 1.8 million tons of fallen tower debris at the site known as "Ground Zero". Handling more than two hundred trucks from multiple contractors delivering loads to five different dumpsites was an arduous task. The DDC therefore used a GPS-based automatic vehicle location system in managing debris removal. The system included a broadband communications network, a camera monitoring and time-lapse recording system, a GPS-

based vehicle tracking system, and a high-speed Internet service to provide access to related data. The system provided a near real-time view, including graphically mapped presentations of trucking operations on a macro level. Users in the field could access information over the Internet to view vehicle location, history reports, and movement tracking. At the end of the project, they found that this GPS-based technology yielded greater efficiency than traditional paper tickets. [10].

4 INDOOR LOCATION INFORMATION

Although GPS is well known for its ability to provide accurate positioning when used outdoor, it was never intended for indoor environment. Besides the fact that the satellite signals are not strong enough to be used inside a building, RF noise and metallic objects positioned inside the building can cause interference and deflection of satellite signals that lead to miscalculated positioning. Nevertheless, many developers have tried to find a way to make GPS work inside buildings. A location support system that operates inside office buildings and homes has the potential to fundamentally change the way human interacts with their immediate environment.

The Active Badge system, one of the earliest indoor location tracking systems, was developed between 1989 and 1992 by the Olivetti Research Laboratory [11]. The Active Badge system provides individual locations within a building by determining the location of their Active Badge. This Active Badge has a globally unique code that is periodically broadcasted through an infrared interface every 10 seconds. Networked sensors placed around the building would detect these transmissions and relay information over a wired network to the central database. The location of the badge can thus be determined on the basis of information provided by these sensors. Privacy issues and its high maintenance costs of the wired network are disadvantages of this technology.

After the Active Badge was developed, AT&T Laboratories Cambridge found that some applications require 3D location and orientation information, which Active Badge cannot supply. In 1997, the new 3D ultrasonic location system, the Bat system, was thus developed for this purpose. The Bat system uses ultrasonic signals to identify the user's location. A short pulse of ultrasound is emitted from a transmitter attached to the object to be located. Each transmitter has a unique 48-bit code and is linked with the fixed location system infrastructure using a bidirectional 433MHz radio link. The receivers used to detect the ultrasonic signals are installed in a square grid, 1.2m apart, above the tiles ceiling and are connected by a high-speed serial network. These receivers would measure the times-of-flight of the pulse and calculate the distances from the transmitter to each receiver. With three or more distances, the system can compute the 3D position of the transmitter. By finding the transmitter's positions for multiple times, the system can calculate its orientation. One disadvantage of the Bat system is the expensive wiring infrastructure used to relay information collected by the receivers to a central computer for processing and back to the user's handheld device [12].

The UNC HiBall Tracker system uses relative ceiling panels housing infrared Light Emitting Diodes (LEDs). A miniature camera cluster called a HiBall looks upward to view infrared LEDs installed in ceiling panels and converts individual LED sightings into position and orientation data. Using known location of the LEDs, the system computes and reports the user's position and orientation. The HiBall Tracker system resolves linear motion of less than 0.2 mm and angular motions under 0.3 degrees without distortions. Although this system yields highly accurate readings, it requires extensive wiring, which makes it expensive and difficult to deploy [13].

RADAR, developed by Microsoft, uses a standard off-the-shelf wireless network technology (IEEE 802.11b) to locate and track user. The RADAR system works by installing access points overlapped throughout the building. The system's administrator then measures and collects the signals' strength in each reference point to create a Radio Map. The Radio Map is a database of locations in the building and the estimated signal strength at each location. To identify the user's location, the system compares the signal strength from the user's mobile device to the Radio Map. Therefore, the nearest point on the Radio Map is identified as the user's current location instead of the real user's current position [14].

As opposed to previous development, the Cricket system, developed by Networks and Mobile System (NMS) research group at the Massachusetts Institute of Technology (MIT), allows applications running on user devices to learn their physical location [15]. The Cricket system consists of beacons and a listener. The beacon is a wall and ceiling mounted unit that emits a radio frequency (RF) wave and ultrasonic pulse. The listener is a unit attached to a user's mobile device and listens for RF wave and ultrasonic signals that the beacon publishes through a building. When the listener hears the RF signal, it turns on its ultrasonic receiver to listen for the ultrasonic pulse. Because the speed of sound in air is much slower than the speed of electronic wave in air, the listener uses the time difference between RF wave and the ultrasonic signal to determine the distance of the beacon. The listener sends information to the mobile device through the serial port. To determine the user's current location using this application, the listener has to obtain at least three estimated distances. Through these values, the application that runs on the user's device will then calculate the user's current location by using the triangular rule.

However, it is also possible for the listener to misinterpret ultrasonic pulses that is radiated from different beacon sources, consequently causing a miscalculation in the distance [12].

5 DEVELOPMENT OF PROTOTYPE APPLICATION

Our group determined to use the Cricket technology to develop a prototype location-based indoor facilities management system. Using schematic drawings obtained from NMS research group at the MIT, our group has fabricated ten beacons (Fig. 1) and two listeners (Fig. 2).

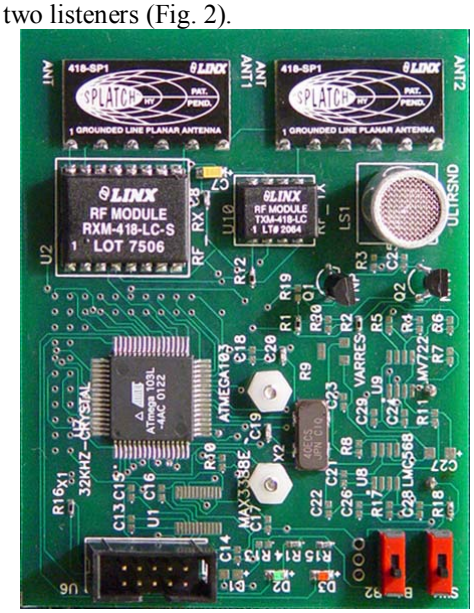

Figure 1. Cricket beacon

Figure 2. Cricket listener

Beacons and listeners were programmed for specifying their location names and ID numbers. Beacons were then mounted on the wall as shown in Fig. 3.

Figure 3. Beacon mounted on the wall

The prototype location-based indoor facilities management system consists of two computer applications. BeaconConfig, developed by the NMS group, is a Java application that retrieves data from the listener and calculates the time different between radio frequency wave and ultrasonic signal to determine the distance of the beacon. Once the listener detects signals emitted at least by three beacons, the BeaconConfig calculates user's current location using triangular rule. Our group added additional function, FMInfo, to BeaconConfig in order to transmit the listener's location information to the Web server. Fig. 4 and 5 show the user interface of BeaconCongif and FMInfo menu.

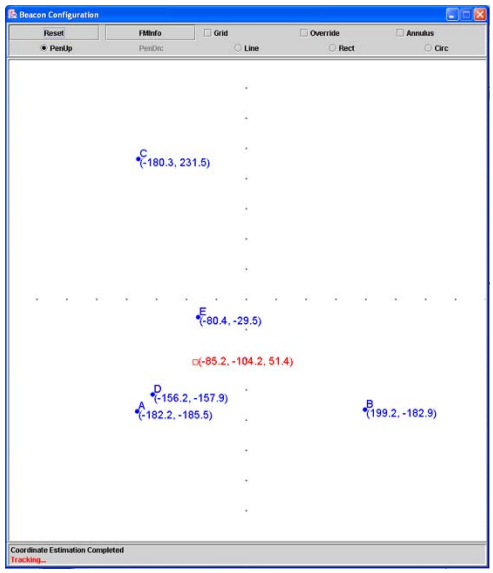

Figure 4. User interface of BeaconConfig

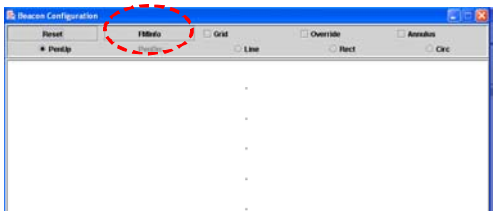

Figure 5. FMInfo button of BeaconConfig

Our group then developed a Web-based application, using Active Server Pages (ASP), to retrieve facilities management information from the database in the Web server. This Web-based application is called when the user clicks the FMInfo button in BeaconConfig. Once the user's location information is transmitted to the Web-based application, it searches database in the server, retrieves inspection data of facilities within a certain boundary, and displays them in the Web page as shown in Figure 6.

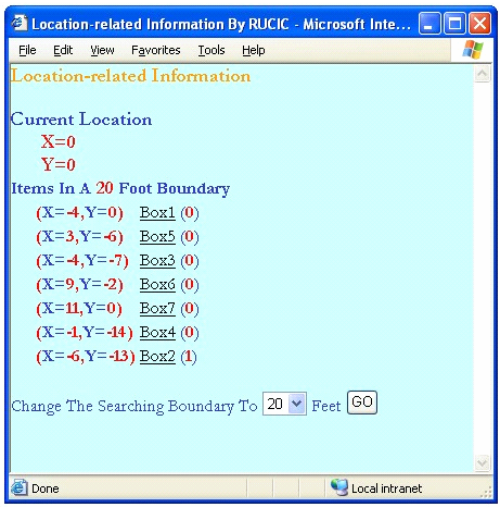

Figure 6. Inspection data retrieved

When the user clicks the object's hyper-linked name, detail object information including pending work order records and additional work order tasks are provided as shown in Figure 7.

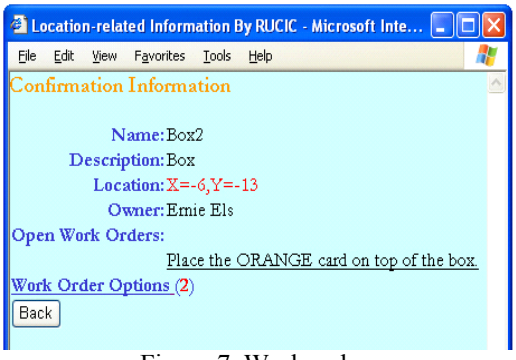

Figure 7. Work orders

If the user wishes to add work order to the object, one may click the hyper-linked "Work Order Options" menu to bring another page as shown Figure 8.

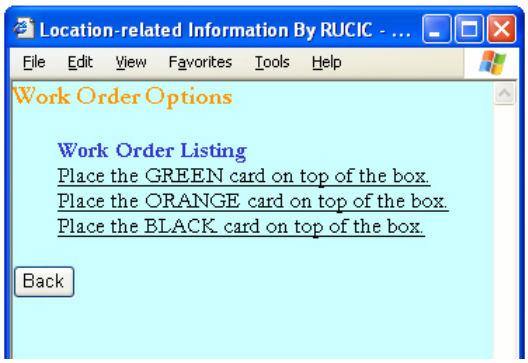

Figure 8. Work order list

This screen displays available work orders with associated links that provide further detailed information on that item of work. If the user clicks a hyper-linked open work order description, a detailed information page concerning that work order is displayed as shown in Figure 9. This page has a function to open or close the work order.

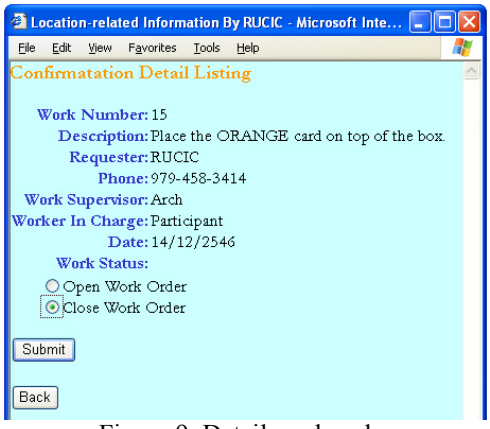

Figure 9. Detail work order

6 TEST OF PROTOTYPE APPLICATION

Our group tested the usefulness of the prototype location-based indoor facilities management system with 10 graduate students majoring construction management. Experiment participants were asked to locate a specific box among boxes scattered in a relatively large open space and conduct a simple task such as placing a magazine on the box using a paper-based instruction or our prototype location-based indoor facilities management system. Students finished given tasks almost 100% correctly when they used location-based system. However, when students were given paper-based instruction, only 40% of work orders were performed correctly. All experiment participants agreed that location-based indoor facilities management would improve facilities management inside a building. However, the test also revealed that the location information identified by the Cricket system was unstable, which made the process of collecting location information difficult. Our group also learned that the NMS group at MIT was developing the second version of the

Cricket system, which may produce more robust signals.

7 CONCLUSIONS

The prototype location-based indoor facilities management system presented in this paper has demonstrated the usefulness of indoor location information in facilities management. Although the Cricket system employed was not robust enough to produce consistent location information yet, indoor location information could be applied to many things such as punch list management. The new version of the Cricket system may prove to be more robust than the current version and will need to be tested again. Once the capacity of the system is enhanced, another experiment should be set up in a larger open space such as indoor stadium. This new experimental area would better mimic the true intent and usage of the technology as applied in the built environment.

Acknowledgments

Our group appreciates generous supports from Dr. Hari Balakrishnan at MIT and his lap members for our investigation.

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Efficient Localization System for Mobile Agents Using Active Beacons

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Abstract In this paper we propose an efficient method of localization for mobile agents by using the active beacon. Active beacons include the ultrasonic sensor, RF module and 8bit microprocessor. Existent systems have the constraint that one beacon cannot cover wide area since ultrasonic sensors have limits in the angle of signal (beam-angle) on which their signal strength depends. We make the beacons active by adding pan-tilt mechanism. In this way, we can use the strongest signal of the ultrasonic waves. As a result, the accuracy of active beacon system has been improved. And it is possible to measure local positions in wider area with this system than with existent beacon systems. In addition, this system is inexpensive because it can decrease the number of beacons by about the half of the existent system.

Keywords: active beacon, mobile agent, indoor localization, time of flight, ultrasonic, pan-tilt

1. Introduction

Recently, The indoor localization problem for the specific mobile agents, such as industrial robots of the factory, home service robots, the toy robots and motion recognition systems, have been getting highly interested. And many researches about the topic have been taken through various kinds of method. For example, there are dead-reckoning, vision method and beacon (ultrasonic sensor) method, and so on.

Dead-reckoning may be the simplest localization method [1] which is, however, fraught with many factors of error such as slippage and backlash. And vision system can be only one solution for a new environment with no prior information. But it is expensive since it is required to make high computation possible for image-processing [2].

Beacon method has good efficiency in cost-saving, easy signal-processing and accuracy [3-4]. But several factors remains to be improved for the higher efficiency. First, the existent systems have some constraints which need the sequential shoot of the signal in order to avoid interferences. Second, the area that one beacon can cover is not wide since ultrasonic sensors have constraints in the beam-angle on which their signal strength depend [5-6]. Consequently, the area in which we can perform the valid localization with one section of beacons (3 beacons) is strongly limited. Third, in case of multiple mobile agents, the efficiency of localization for fast agents would be relatively decreased if the systems' sampling time is fixed to all the agents.

In this paper, we propose two methods to solve the problems of the existient systems. First, making beacons active by adding pan-tilt mechanism, we are to solve the first two problems. As mentioned above, the ultrasonic sensors have the limited beam-angle. However, if we use the active mechanism in the multi-agents' localization, we can rotate one beacon toward some mobile agent while the other beacon toward other agent according to the judgement of RF beacon (beacon with Radio-Frequency module installed) and can transmit the ultrasonic signals with no interference. In this way, we can transmit the ultrasonic signals to the multiple mobile objects simultaneously. Therefore, wider area can be covered with the same number of beacons in the proposed localization. Second, RF beacon receives the data about each agent's velocity as well as position via RF communication from the agents. Also, the RF beacon gives a priority – how often to make localization – which is based on the velocity of the mobile agents: it gives higher priority to faster object. Hence, the sampling time is changed efficiently corresponding to the velocities of mobile agents.

This paper decribes Structure of system and basic concepts (section 2), Inverse kinematics for active beacon (section 3), Dimensional localization using Newton method (section 4), Experimental results (section 5) and Conclusion(section 6).

2. Structure of system and basic concepts

1.1 Basic concept of system

Figure 1 shows the usable area with the existent beacon method. Basically, our active beacon method has a similar structure with the existent beacon system except some following aspects.

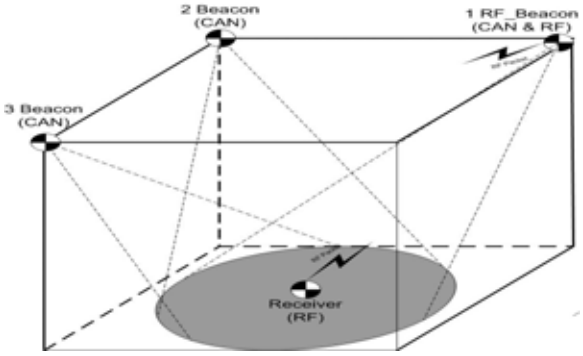

Figure 1. Usable area with fixed angle

There is timing synchronization with radio frequency communication between the RF beacon and receiver for measuring TOF (Time-Of-Flight). In this case, radio frequency communication is only used to fire beacons on existent beacon system. But it furnishes the RF beacon with some information of receiver such as velocity and position of mobile agents. RF beacon gives a priority based on the velocities of mobile agents and sends transmission-permission-packet to them through the RF module. And it transmits the ultrasonic signal which is necessary for a localization of mobile agents by the priority. If we use this method, sampling time is changed by each velocity of mobile agents. Therefore, the density of localization for mobile agents is regularly maintained. Also RF beacon and beacons turn to the mobile agents by computing inverse kinematics before they transmit ultrasonic signal.

When each beacon completes transmission of ultrasonic signal, the receiver which is installed to each mobile agent calculates distance from the corresponding beacon. Then, the mobile agents compute local position by Newton Method.

Also, each RF beacon sends the information of neighboring section to mobile agents at boundary of section resulting in that mobile agents can continually obtain a local position even when moving section to section.

1.2 structure of hardware

- Receiver, RF beacon and Beacon (Figure 2):

Most electronic elements are commonly used for receivers, RF beacons and beacons. All modules include 8bit microprocessor with CAN controller. Furthermore, receivers include tone decoders for ultrasonic signal's detection. And radio frequency modules of 447MHz are included in only both receivers and RF beacons, and ultrasonic transmitters are included in only both RF beacons and beacons.

Receivers are connected with mobile agents through CAN or RS-232 while RF beacons are connected with beacons through CAN. Major function of beacons is firing the ultrasonic signal when they receive a command of firing from RF beacon.

Figure 2. Receiver, RF beacon and Beacon

- Pan-tilt mechanism:

Figure 3. Pan-Tilt Mechanism

Figure 3 shows pan-tilt mechanism, having two degree of freedom, to which RF beacons and beacons are attached. Hence, RF beacons and beacons are possible to target on mobile agents located at any position of current area. Beacons are attached to the indoor space with free configuration. But RF beacons must know the attached position of beacons and themselves in section because they must furnish the information of positions to receiver. Table 1 shows configuration of hardware for each module. And figure 4 shows the usable area which is used the active beacon.

	Receiver	RF beacon	Beacon
RF module	O	O	C
CAN Controller	X	O	O
US transmitter	X	O	O
US receiver	O	X	X
Pan-Tilt	X	O	O

Table 1. Configuration of hardware

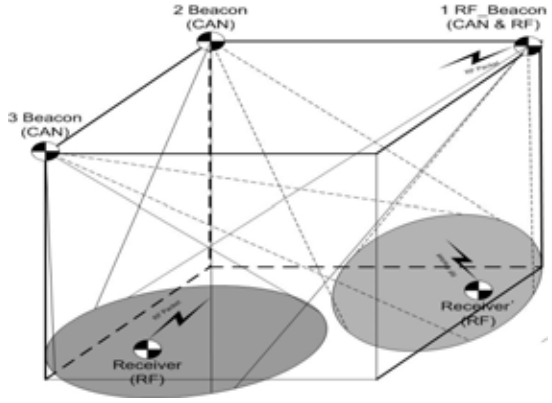

Figure 4. Usable area with active beacon

3. Inverse kinematics for active beacon

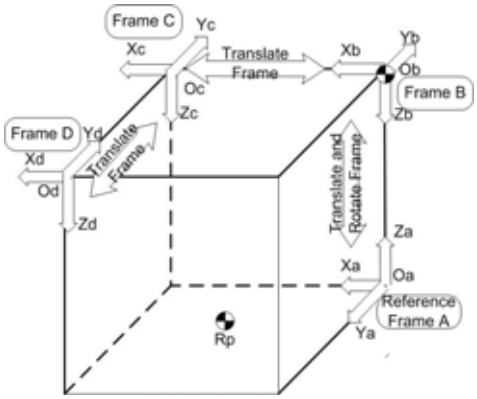

Figure 5. Coordinate frame for kinematics

Figure 5 shows translation and rotation from reference frame A to frames B, C and D of each RF beacon and beacons. Rotations from reference frame fix on 180 degree for X axis, because it can reduce the amount of computation.

For example, Frame B translates as $O_b(x_{Ob}, y_{Ob}, z_{Ob})$ and rotates as $(180^o, 0^o, 0^o)$ from frame A. In this place, O_b is the central coordinate of frame B and position of beacons too. So ${}^{A}R_p(x_A, y_A, z_A)$ that is receiver's position in frame A is expressed ${}^{B}R_p(x_B, y_B, z_B)$ that is receiver's position in frame B such as Eq. (1)

$$
\begin{aligned}
{}^{A}R_p &= {}^{A}T_B \, {}^{B}R_p \\
{}^{B}R_p &= {}^{A}R_B^{-1} \, {}^{A}R_B
\end{aligned}
\tag{1}
$$

${}^{A}T_B$ is homogeneous transformation matrix from frame A to frame B. So, we obtain the solution of Eq.(1)

$$
{}^{B}R_p = \begin{bmatrix} x_p - x_{Ob} \\ -y_p - y_{Ob} \\ -z_p - z_{Ob} \\ 1 \end{bmatrix}
\tag{2}
$$

We are able to calculate angles of joint1 and joint 2 using this solution. When θ_1 is angle of joint 1 and θ_2 is angle of joint 2, we obtain the solution by Eq,(3).

$$
\begin{aligned}
\theta_1 &= \tan^{-1}\left(\frac{-y_p - y_{Ob}}{x_p - x_{Ob}}\right) \\
\theta_2 &= \tan^{-1}\left(\frac{\sqrt{(x_p - x_{Ob})^2 + (-y_p - y_{Ob})^2}}{-z_p - z_{Ob}}\right)
\end{aligned}
\tag{3}
$$

Figure 6 shows joints of pan-tilt mechanism.

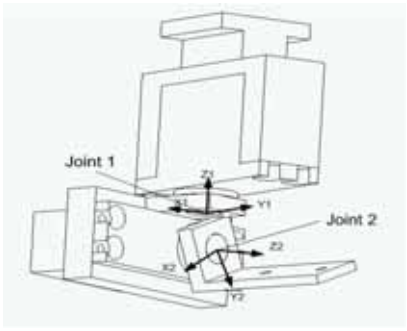

Figure 6. Coordinate Frame in Pan-tilt

4. 3 dimensional localization using Newton method

First of all, receiver measures the distances, r_i from at least three beacons including RF beacon. Figure 7 shows method of localization.

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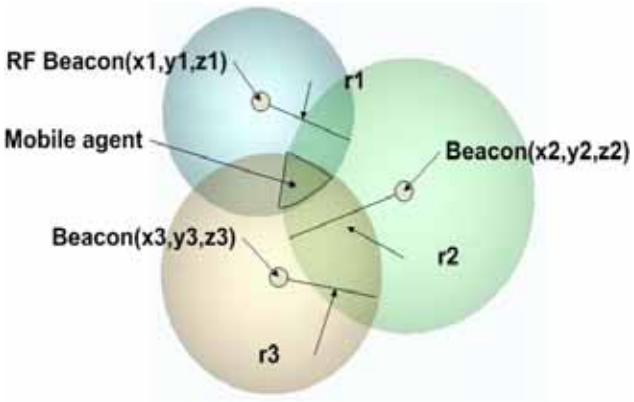

Figure 7. Concept of Localization

Define a position vector as

$$\mathbf{x} \triangleq [x\ y\ z]^T \tag{4}$$

Given the beacons' positions, $\{\mathbf{x}_1, \dots, \mathbf{x}_n\}$, equations w.r.t receiver's position $\mathbf{x}$ are expressed as

$$\|\mathbf{x}-\mathbf{x}_i\|^2 = r_i^2, \quad i=1,\cdots,n \tag{5}$$

If we define $F(\mathbf{x})$ as

$$F(\mathbf{x}) \triangleq [\, f_1 \cdots f_n \,]^T, \qquad f_i = \|\mathbf{x}-\mathbf{x}_i\|^2 - r_i^2 \tag{6}$$

then localization problem is equivalent to solving the following equations

$$F(\mathbf{x}) = [0 \cdots 0]^T \tag{7}$$

Since, given a $\mathbf{x}^{(k)}$ and its neighborhood $\mathbf{x}^{(k+1)}$, the $F(\mathbf{x}^{(k+1)})$ can be approximated by Newton method like

$$F\left(\mathbf{x}^{(k+1)}\right) \cong F\left(\mathbf{x}^{(k)}\right) + F'\left(\mathbf{x}^{(k)}\right)\left[\mathbf{x}^{(k+1)} - \mathbf{x}^{(k)}\right] \tag{8}$$

where

$$F'\left(\mathbf{x}^{(k)}\right) = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial z} \\ & \vdots & \\ \frac{\partial f_n}{\partial x} & \frac{\partial f_n}{\partial y} & \frac{\partial f_n}{\partial z} \end{bmatrix} \tag{9}$$

Then, the solution is computed by iteration with a proper tolerance like

$$\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} - \left(F'\left(\mathbf{x}^{(k)}\right)\right)^* F\left(\mathbf{x}^{(k)}\right) \tag{10}$$

where the A^* means the pseudo inverse of A.

5. Experimental results

5.1 Experimental environment

Next following figures show the simple top view of experimental space and picture of real experimental space. Active beacon rails are established on a ceiling for the flexibility in beacon's position. Also they are efficiently mounted for attaching pan-tilt mechanism. Red circles in the picture describe the active beacons established on the ceiling

Points of Experiment				
1	2	3	4	5
(500, 2500, 500)	(500, 500, 500)	(2500, 500, 500)	(2500, 2500, 500)	(1500, 1500, 500)

Table 2. Coordinate in Reference frame (fixed angle)

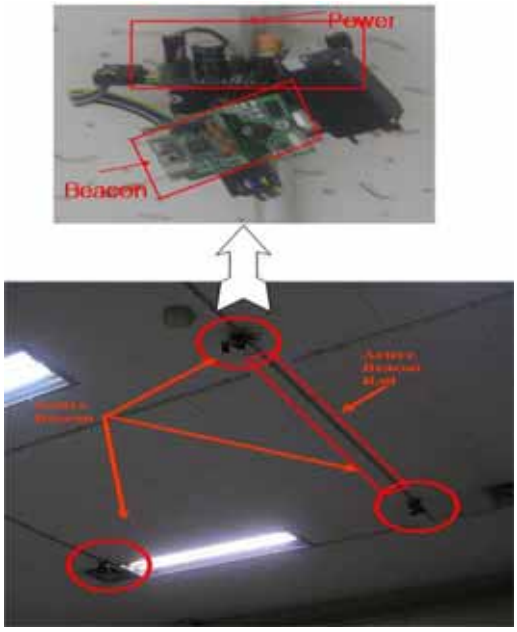

Figure 8. Active beacon and Beacon set

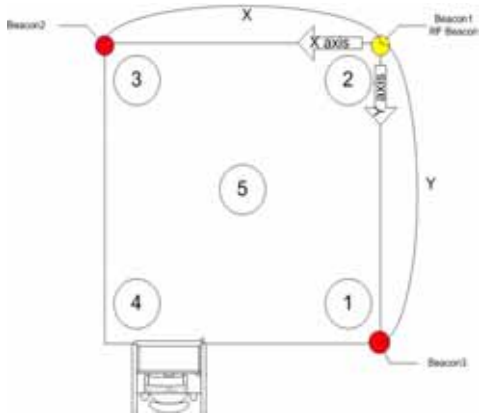

Figure 9. Simple top view and test position

5.2 Experiment with fixed angle

We obtain the results such as table 3 and figure 10 which are experimented in 3000mm of X length and 3000mm of Y length (Through all the results, the basic unit is millimeter). Circles of 1 to 5 in Figure 8 show points of experiment and its coordinates are shown in Table 1. Experiments have been performed 10 times per each point of experiment. Table 3 shows the successful receiving rate of ultrasonic signal on each point. Also Figure 10 shows local position's error of each point.

BeaconID	Successful receiving rate on each point (unit: %)				
	1	2	3	4	5
1	100	100	100	100	100
2	80	100	100	40	100
3	100	100	100	100	90

Table 3. Successful receiving rate on each point (fixed angle)

We can find out the bad result at point 4, because all of beacons are targeted to point 5. As mentioned above, ultrasonic signal which reached point 4 should be weak since ultrasonic sensor has the limited beam angle. On the other hand, weak ultrasonic signal gives a bad effect on the accuracy of localization. In this experiment, ultrasonic sensors have firing time of 450us at least which is required for the tone decoder of receiver. The weak ultrasonic signal is detected latter than the strong signal resulting in that it causes large, values of error as shown in Figure 10.

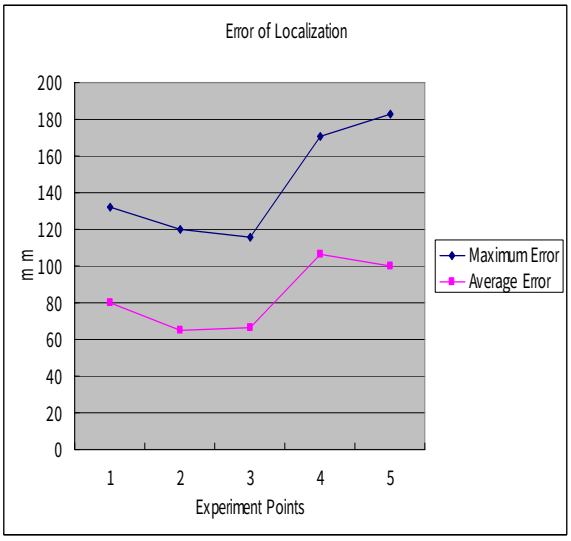

Figure 10. Maximal and Average Error with fixed angle

5.3 Experiment with variable angle(active beacons)

Experiments of active beacon system are executed in a space whose size is 4000mm by 5700mm and table 4 and figure 11 show the results of experiments.

beacon ID	Successful receiving rate on each point (unit: %)				
	1	2	3	4	5
1	100	100	100	100	100
2	100	100	100	100	100
3	100	100	100	100	90

Table 4. Successful receiving rate on each point (active beacons)

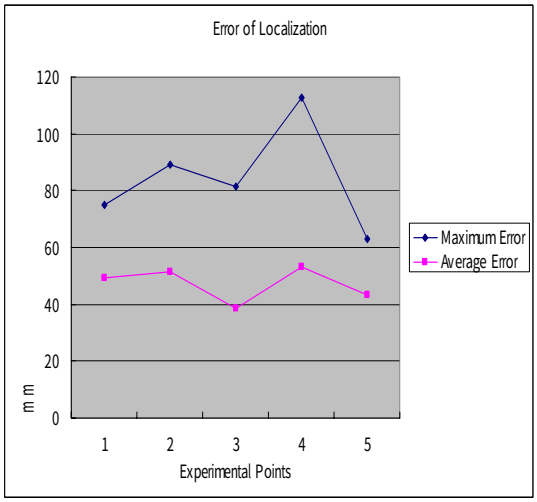

Figure 11. Maximal and Average Error with variable angle (active beacons)

As we expected, both the successful receiving rate and the accuracy in the active beacon system are better: maximal and average errors are reduced by a half and the successful receiving rates remains high even at the point 4.

5. Conclusion

Beacon system which is one of localization's methods is very good for cost-saving, accurate localization. We have performed experiments with the existent method which has a fixed angle. And we can find out the problem of the existent beacon method. As mentioned above, existent researches of beacon method are not efficient. Hence, we propose the active beacon system in this paper that attaches beacon to pan-tilt mechanism. As shown in the results, active beacon system is better than the existent beacon system in two factors – both the successful receiving rate and the accuracy of localization. Naturally, this system is not perfect up to now. Average error is over the 30mm and maximal error over the 60mm.
However, we confirm the possibility for efficient localization. And the accuracy and the successful receiving rates heavily depend on the electronic circuits and software's delay. The delay by software is factor of error each distance between receivers and beacons.

We will make maximal error under 50mm.In addition and make the area which one set of beacon covers over 6m by 6m. So we are planning to use our active beacon system in the building for the localization of mobile robots. Then, they can detect their absolute positions by themselves, and also can have the flexibility on their free movements.

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XSFORM: A SCHEMA-DRIVEN FORM-BASED XML INFORMATION PROCESSOR

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Abstract: A form-based XML information processor, named XsForm, has been developed in this work. XsForm takes an XML schema as input and generates the corresponding Windows forms automatically to facilitate gathering, editing, sharing, and management of XML information. The information processed in XsForm is then saved into a well-formed and valid XML file for further e-business applications. This paper discusses the development of XsForm and its application to promote e-business in the construction industry.

Keywords: XML, Schema, UIML, Form-based information processing, e-business.

1 INTRODUCTION

To promote information sharing and exchange on Internet among collaborative parties in the e-business process, many industries, including the construction industry, have made considerable efforts on information standardization using the XML (eXtensible Markup Language) technologies [1]. The XML Schema [2] technology, in particular, has been extensively employed to standardize shared vocabularies as well as the structure, content and semantics of commonly used documents for a particular industry or area of application. For example, ebXML [3] has been proposed to enable enterprises of any size, in any location, to conduct business using the Internet; aecXML [4] is being developed to represent information in the Architecture, Engineering, and Construction (AEC) industry.

In addition to the information standards (in terms of standard schemas), an information processing tool is needed for people to gather, digitalize, edit, and save the data for a given XML schema. The most common approach used by this kind of tools to ease the data processing tasks is the use of a form-based Graphical User Interface (GUI). Although the GUI and its associated functions of this kind of tools are similar, people often spend repetitive efforts on developing new tools or modifying/extending old tools whenever they need to deal with XML documents (files) of different schemas.

To help building the XML information processing tools, several related research and commercial efforts have been made. For example, XQForms [5] is a Web-based GUI builder to generate a query form and reports for XML data. GuiGen [6] provides a comprehensive set of tools for creating form-based GUI applications on Windows. Microsoft InfoPath [7] is a commercial product that provides familiar Microsoft Office System environment for the users to create forms solutions, using existing customer-defined schemas, for gathering and editing XML information in the WYSIWYG (What You See Is What You Get) way. In addition, a W3C specification called XForms [8] has been proposed that combines XML and forms to offer a better alternative to HTML-based forms. Several XForms engines have been developed to support the applications of XForms.

Although the aforementioned efforts have provided useful tools to ease the task of building form-based XML information processing applications, fair amount of repetitive development efforts on form-based GUI is still not avoidable when the user needs to deal with XML documents of different schemas. To address this problem, this research has developed a form-based XML information processing application, called XsForm, that is driven by the user-input XML schema to automatically generate appropriate Windows forms and associated functions. This paper discusses the development of XsForm and its application to promote e-business in the construction industry.

2. SYSTEM ANALYSIS AND DESIGN

The major requirements for development of XsForm are the following:

- The system should build an appropriate form-based GUI automatically based on the user-input XML schema to facilitate the gathering, editing, and management of XML information associated with the schema. In addition, the system should allow input of a new schema at any time and rebuild its form-based GUI accordingly and automatically.

- The system should provide some flexibility for the user to adjust the appearance of GUI.
- The system should provide functions for saving the information into an XML file that is well-formed and valid with respect to the user-input XML schema as well as for searching and querying XML information in the XML files managed by the system.

According to the requirements discussed above, the architecture of XsForm is designed as shown in Fig. 1. The arrows in Fig. 1 show the data flow between the user, the XsForm functional components (in the business logic tier and UI tier), and the XsForm functional components (in the data tier). XsForm takes an XML schema as input and uses the Schema2UIML component to parse and transform the XML schema into the corresponding UIML file. UIML (User Interface Markup language) [9], an XML language for defining user interfaces, is employed in this work to describe and record detailed information about the required GUI. The recorded information is then used by the UIML2GUI component to create Windows forms and associated functions. The above process from the input of XML schema to the creation of corresponding Windows forms is performed automatically by XsForm.

The GUI Arrangement component in Fig. 1 provides some options the user to customize the automatically generated form-based GUI. The preferences specified by the user for the options are stored in the Configure file, which is used by the Schema2UIML component to create the UIML file for customized GUI appearance. In addition, the Search GUI component supports full-text search for all XML files in the user-specified file directory and its sub-directories. It also provides customizable advanced search functions for the user to query XML information based on selected tag names in the user-input XML schema.

XsForm can also take a valid XML file as input. In this case, the system finds and loads the corresponding XML schema automatically. The automatically generated Windows forms are then filled with the data of the XML file. XsForm produces XML files as output. All of the XML files produced are not only well-formed but also valid with respect to the user-input schema.

3. SYSTEM IMPLEMENTATION

This work uses the Microsoft VisualBasic.NET with .NET Framework to implement XsForm. In this section, discussions are focused on the implementation of the two most important components in XsForm: Schema2UIML and UIML2Schema.

3.1 Schema2UIML

Schema2UIML is mainly a parser that transforms an XML Schema into a corresponding UIML file. The XML library, called System.xml, provided by the Microsoft .NET Framework is used to implement Schema2UIML.

Schema2UIML should be able to deal with most of the XML Schema syntax (including the nested structure), and map different types of elements in the schema into appropriate corresponding Windows form widgets. Because of the structure of most XML Schemas has no more than three layers (the root element not included) as illustrated in Fig. 2, the following rules can be used to automate the mapping between the XML Schema and Windows form widgets (see also Table 1 and Fig. 2):

a. The root node in the XML schema usually has the name or title of the schema. This research converts the root node into a base Windows form and takes the value of root element as the title of the window.

b. The child nodes of the root element usually represent classification groups, each of which has some sub-elements with similar properties. Therefore, these similar elements are grouped and presented together in the same window by Tab Control or Tab Pages.

c. The elements in the second layer of the schema structure tree contain detailed information of a classified group. These elements have various kinds of data types, such as string, integer, Boolean, and date. They also can be transformed into proper Windows form controls, such as textbox, label, combo-box, and month calendar (see Fig. 3).

d. If the third layer exists, those elements may contain more detailed information than those of the elements in the second layer. The mapping rules are the same as those in the second layer. If there are more than one element belonging to the same parent-element (for example, a person may have more than one phone number), the Group-Box widget is used to enclose those elements.

An example transformation by Schema2UIML is shown in Fig. 4. Figure 4(a) shows the fragment of an example XML Schema. The transformed UIML contents are shown in Fig. 4(b).

3.2 UIML2GUI

The UIML file produced by Schema2UIML has already recorded the structure of user interface and information about what components should be used to represent the elements of different types in the schema. It is then the responsibility of UIML2GUI to construct the actual Windows form widgets based on the description in the UIML.

UIML2GUI is implemented as an MDI (Multiple Document Interface) container to support review and editing of multiple XML files in the same window as well as to facilitate file management and comparison.

Figure 5 shows an example user interface generated by UIML2GUI. In this example, there are 19 pages of TabCobtrols in total on the top of the Windows form. The Windows form controls employed on the selected tab page include the Label, TextBox, and ComboBox, etc. In addition, a grid-style interface is automatically added by the system to assemble data grids at the bottom of each tab page with an "update" button to facilitate the management of data.

4. SYSTEM APPLICATION

An example is provided here to demonstrate how XsForm can be used to promote e-business in the construction industry.

Assume that a set of paper-based forms required in the construction process needs to be converted into a set of electronic forms in order to perform e-business tasks. Also, there is a need for a tool to collect and digitalize data for the set of forms and store the data in the desired XML format. As shown in Fig. 6, the application of XsForm to help the situation in an effective and efficient way is described in the following steps:

1. Define an XML schema to describe the structures, contents, and semantics of the set of forms. Although this step requires some fair amount of efforts, the resulted XML schema is the key document for sharing and exchange of the information in the set of forms with collaborative parties in the e-business process.
2. Execute XsForm and read the XML schema into XsForm.
3. XsForm automatically and quickly generates appropriate Windows forms for the user to digitalize and edit data in the forms. It also allows the user to save the data in the XML files that is well-formed and valid with respect to the given XML schema.
4. The XML files and the XML schema can then be used in the e-business process for information sharing and exchange.

It can be seen that XsForm significantly eases the task of collecting and editing electronic information that is usually the first step toward information sharing and exchange in the e-business.

5. CONCLUSIONS

A schema-driven form-based XML information processor, called XsForm, has been developed in this work to facilitate gathering, editing, sharing, and management of XML information. XsForm generates Windows forms with associated functions automatically according the user-input XML schema. It helps to save repetitive efforts on development of similar but independent form-based applications, each for processing information in XML documents associated with a particular schema. XsForm has also been shown to be an effective and efficient tool to ease the task of collecting and editing electronic information and to promote information sharing and exchange in the construction industry.

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Table 1 The mapping rules employed by Schema2UIML

XML Schema	UIML
Root node	Windows Form
First layer	TabPages
【String】、【Integer】in the second and third layers	Label＋TextBox
【Boolean】	ComboBox
【Date】	Month Calendar
Third layer element	Group Box

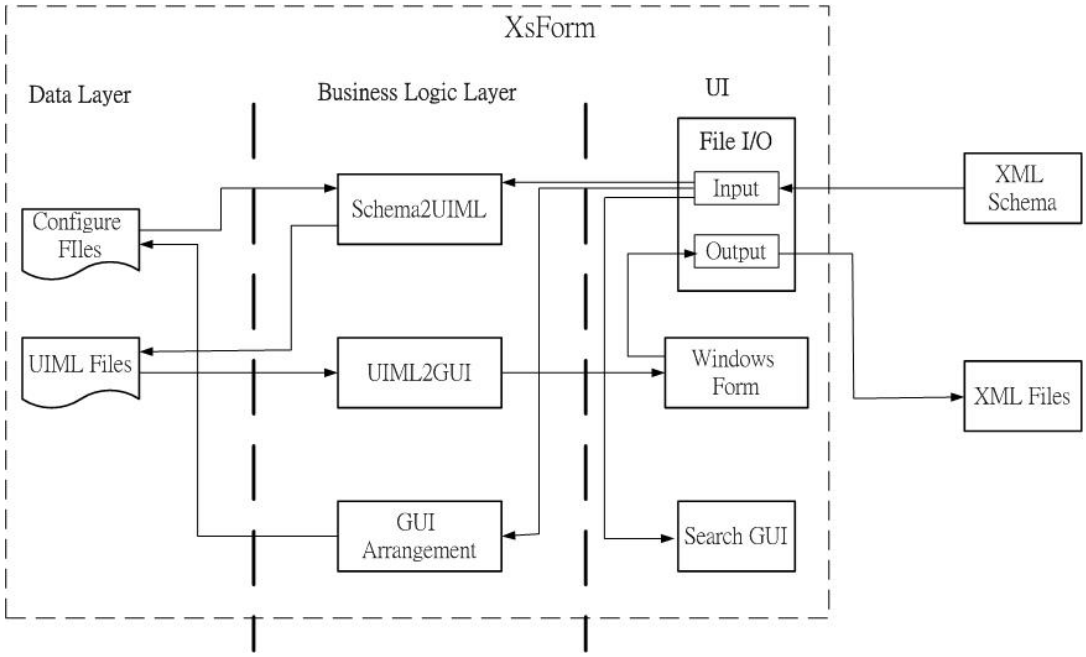

Figure 1 XsForm's Architecture.

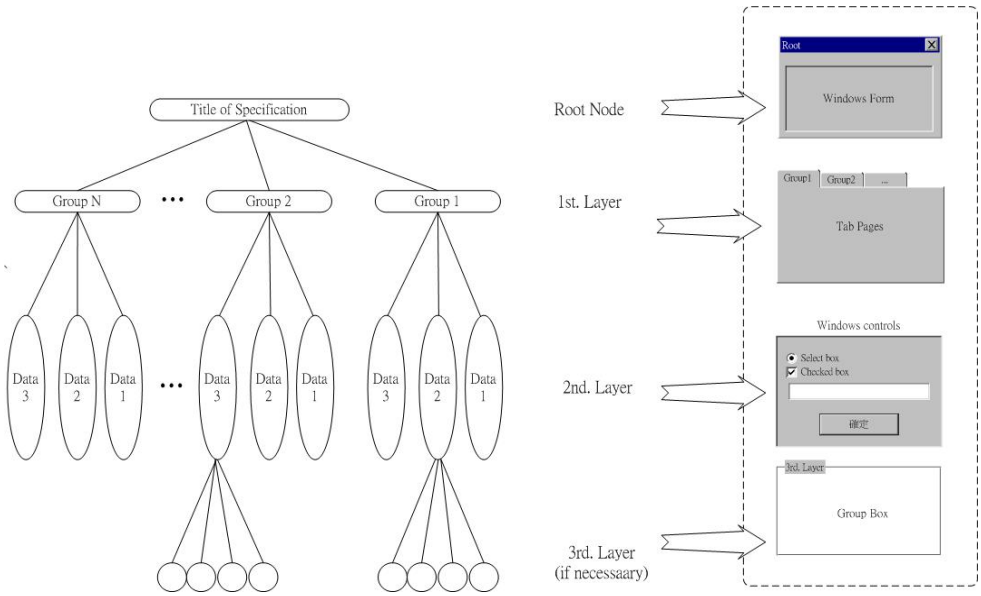

Figure 2 Transformation from XML Schema to UIML.

Figure 3 ComboBox and MonthCalendar GUI

```
<xs:complexType name="Owner">
- <xs:sequence>
    <xs:element name="ID" type="xs:integer" minOccurs="0" />
    <xs:element name="Name" type="xs:string" minOccurs="0" />
    <xs:element name="Agent" type="xs:string" minOccurs="0" />
    <xs:element name="IdentificationNo" type="xs:string" minOccurs="0" />
    <xs:element name="BirthDate" type="xs:date" minOccurs="0" />
    <xs:element name="Phone" type="xs:string" minOccurs="0" />
    <xs:element name="ContactAddress" type="xs:string" minOccurs="0" />
    <xs:element name="Address" type="xs:string" minOccurs="0" />
    <xs:element name="Fax" type="xs:string" minOccurs="0" />
    <xs:element name="Email" minOccurs="0" />
    <xs:element name="FloorDetail" type="FloorDetail" minOccurs="0" maxOc
  </xs:sequence>
  <xs:attribute name="LFT" type="xs:long" />
  <xs:attribute name="Parent" type="xs:integer" />
  <xs:attribute name="Status" type="xs:integer" />
</xs:complexType>
```

(a) fragment of an example schema

```
<part class="TabPages" id="Owner">
  <part class="Label" id="Owner_ID_label" />
  <part class="TextBox" id="Owner_ID_value" />
  <part class="Label" id="Owner_Name_label" />
  <part class="TextBox" id="Owner_Name_value" />
  <part class="Label" id="Owner_Agent_label" />
  <part class="TextBox" id="Owner_Agent_value" />
  <part class="Label" id="Owner_IdentificationNo_label" />
  <part class="TextBox" id="Owner_IdentificationNo_value" />
  <part class="Label" id="Owner_BirthDate_label" />
  <part class="MonthCalendar" id="Owner_BirthDate_value" />
  <part class="Label" id="Owner_Phone_label" />
  <part class="TextBox" id="Owner_Phone_value" />
  <part class="Label" id="Owner_ContactAddress_label" />
  <part class="TextBox" id="Owner_ContactAddress_value" />
  <part class="Label" id="Owner_Address_label" />
  <part class="TextBox" id="Owner_Address_value" />
  <part class="Label" id="Owner_Fax_label" />
  <part class="TextBox" id="Owner_Fax_value" />
  <part class="Label" id="Owner_Email_label" />
  <part class="TextBox" id="Owner_Email_value" />
  <part class="GroupBox" id="FloorDetail">
</part>
```

(b) the corresponding UIML

Figure 4 a Schema2UIML example.

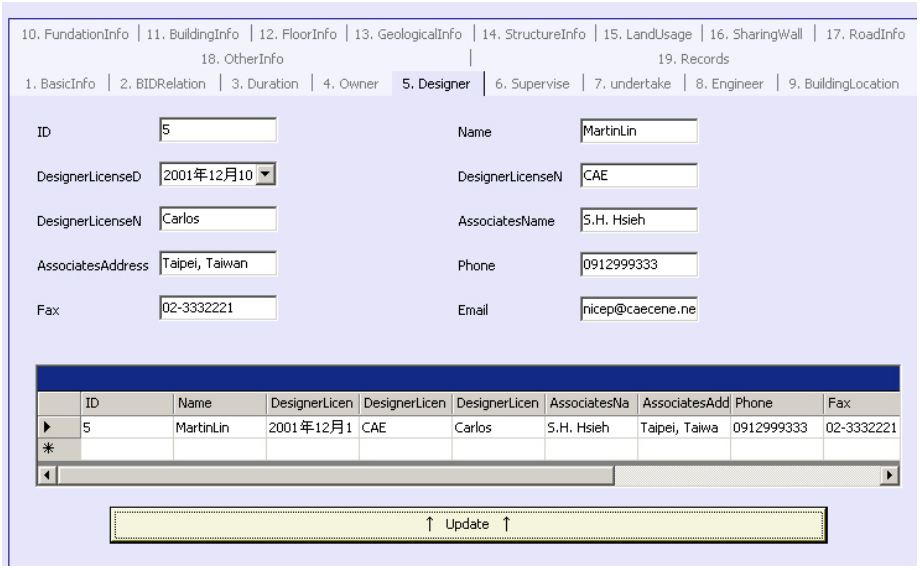

Figure 5 An example user interface generated by UIML2GUI

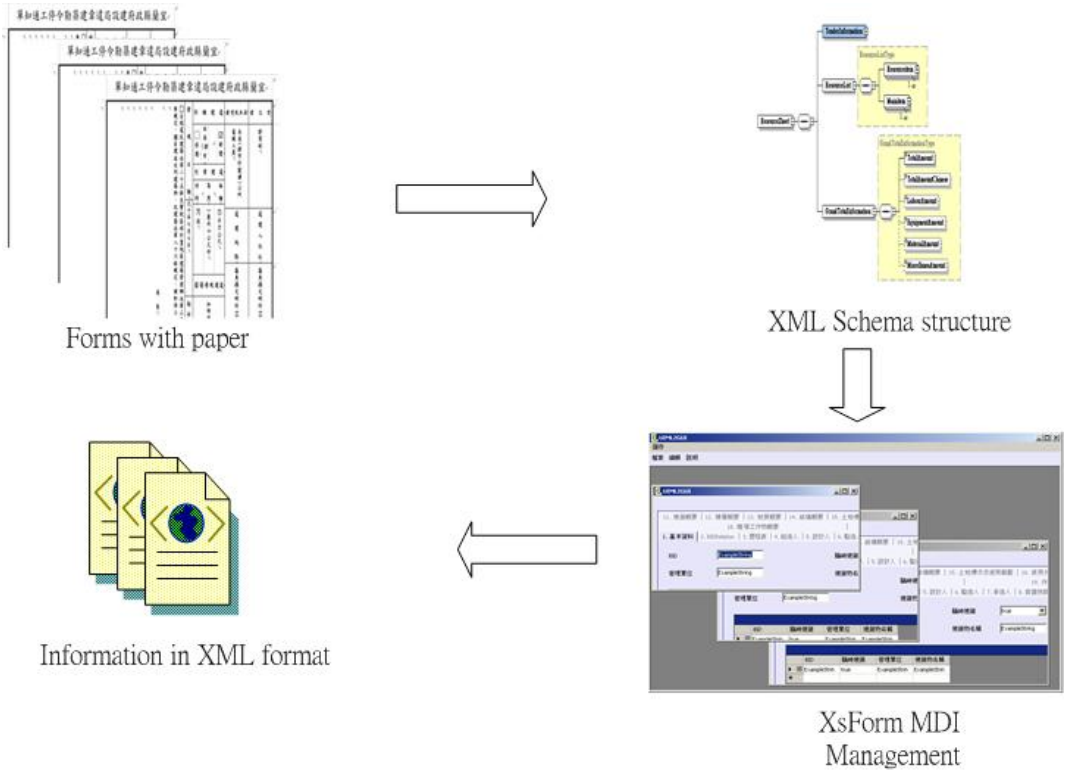

Figure 6 Application of XsForm

METHODOLOGY OF MOBILE COMPUTING IN CONSTRUCTION MANAGEMENT

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Abstract: This paper reports the development of mobile computing in construction management. The paper focuses on the methodology of the development based on EUC. First, the paper indicates the effectiveness of EUC in construction projects. The authors introduce design pattern of user interface and the use of UML for EUC. Secondly, the paper describes the process of development of PDA Inspection Support System for Finish Work with UML. User interface is an interface between users and computer-aided system, and can be one between users and system developers. In the developed system, user interfaces are classified to some design patterns with the use of control function such as list, option button and scroll bar. End users can customize and combine them freely. As a result, they can make their own flowcharts. System developers can build computer-aided systems with them easily and quickly. The paper also shows the effectiveness of the system. Finally, the paper summarizes this methodology and concludes the effectiveness.

Keywords: Construction Management, Mobile Computing, PDA (Personal Digital Assistants), EUC (End User Computing), Design Pattern, UML (Unified Modeling Language)

1. INTRODUCTION

Construction managers have recently handled various types of digital information such as drawings, specification, checklists and daily reports [2, 4]. However, they need to access the real construction site to manage the construction project. They usually use sheets of paper and/or field notes. As a result, they still have a lot of typical and routine jobs in construction site, such as the collection of construction data and the inspection. A gap in time and space between the outdoor construction site and the office occurs [4].

Now the current mobile computing can improve the field work in construction, and enhance the total productivity of construction management. The authors have developed the mobile computer–aided engineering systems, as follows: Inspection System, Position Check System, and Progress Monitoring System [4]. In the paper, the authors made clear the necessary functions for the system through the interview with construction managers, and adopted PDA as a mobile computer. The mobile system is composed of two programs: the data input program in PDA and the output and analysis program in the spreadsheet application software of PC. User interfaces in PDA are mainly for data input, and answer various kinds of data input such as text and number.

On the other hand, construction projects have unique features and limitations. Computer-aided engineering systems for construction projects need the flexibility for each of projects. The authors recognize that the concept of EUC is useful and necessary to achieve it. However, there has been no useful methodology to realize EUC in the development of computer-aided engineering systems for construction projects. There has been no useful tool for it.

This paper aims to establish the methodology of the development of computer-aided engineering systems. The authors indicate two points for EUC. One is the mechanism to acquire the flexibility of system. They pay attention to design pattern of user interface. The other is a useful communication tool between end users and system developers. Common language between them is necessary. They pay attention to the Unified Modeling Language (UML).

2. EUC AND MODELING

As mentioned above, the authors recognize that EUC is useful as a concept corresponding to acquire the flexibility of system. However, it is still unrealistic that end users, construction managers, develop the whole of the computer-aided engineering system for the project. In general, their current literacy for the development of the system is not enough.
The authors have developed the systems by the collaboration of end users and system developers [4, 5]. The development is based on the EUC. EUD (End User Development) may be suitable for this process. That is, system developers prepare all-purpose components of the system in advance. End users customize and combine them freely to execute the construction rationally and effectively. System developers complete the computer-aided engineering system under the basic design. They can develop it quickly and achieve the flexibility for each.

2.1Main Points in Modeling based on EUC

Through the above development of system, the authors understand that the modeling, which both end users and system developers can understand, is necessary. There are two points in the modeling.
One is the mechanism to acquire the flexibility of system. The authors think that it is design pattern of user interface. It is necessary that end users can recognize the functions, controls, and behaviors of model. It is also necessary that they can design the basic structure of the system with the model. On the other hand, it is necessary that system developers can build the system with the model. In other words, the important object in modeling for EUC will be "the object of control" from the view point of end users, and be "the base of design" from that of system developers. Design pattern of user interface can satisfy both requirements.
The other is how to communicate between end users and system developers for the development of the system. Common language between end users and system developers is necessary. A useful communication tool not only between end users and system developers but also among system developers is also necessary.
UML offers nine graphical diagrams that describe the computer system from various kinds of viewpoints. There is some possibility of using UML as the useful communication and design tool.

2.2 Application of UML

The UML is a graphical language for visualizing, specifying, constructing, and documenting the artifacts of a software-intensive system. UML offers a standard way to write a system's blueprints, including conceptual things such as business processes and system functions as well as concrete things such as programming language statements, database schemas, and reusable software components [7]. UML defines some diagrams to describe complex systems at different views.

The authors arranged UML diagrams and set up the modeling flow for this research. Figure 1 shows the flow and the role of each diagram. In this modeling, users are end users or system developers. They are classified in three broad categories. They are basically in ascending order, and are sometimes in parallel one.
The first category is the case study.

1) Description of Use Case: Users arrange actual use cases and define the relationship among them with use case diagram. As a result, the scope of model and system will become definite.
2) Description of Process Case: Users describe a scenario for each use case. Scenario is not a UML diagram. However, the research in JAHIS [3] uses it effectively. It will help the structure of model behavior. So, the authors adopt it.
3) Description of Object Case: Users describe the object diagram for each use case. This will help the construction of class diagram.

The second category is the description of model behavior. In other words, it is the description of dynamic structure of system.

4) Description of Model Process: Users describe the work flow of the model with activity diagram. This will help the definition of scope of computer-aided systematization.
5) Description of Message Flow: Users describe the message flow in the model with sequence diagram. This will help the definition of structure of system.
6) Description of GUI Flow: Users describe the GUI flow with sequence diagram and/or GUI screen. The authors understand that GUI is an important component in EUC, and put it in the modeling in this research, even though it is not a UML diagram.
7) Description of State Transition: Users describe the state transition of the model with statechart diagram. This is especially useful for the description of the repetitive procedure.

Case Study	1	Use Case Diagram	Description of Use Case
	2	Scenario	Description of Process Case
	3	Object Diagram	Description of Object Case
Model Behavior	4	Activity Diagram	Description of Model Process
	5	Interaction Diagram	Description of Message Flow
	6	GUI Flowchart	Description of GUI Flow
	7	Statechart Diagram	Description of State Transition
System Structure	8	Class Diagram	Description of Class Structure
	9	Component Diagram	Description of Software Structure
	10	Deployment Diagram	Description of Processor Structure

Figure 1 Modeling Flow with UML

The last category is the description for the implementation of system.

8) Description of Class Structure: Users describe class structure with class diagram. Class is an abstract concept and is refined through the description of case studies and model behavior.
9) Description of Software Structure: Users describe the dependencies among software with component diagram.
10) Description of Processor Structure: Users describe the configuration of run-time processing elements and the software components.

3. MODELING WITH UML

The paper explains the modeling for the case of the finish work inspection with PDA Inspection Support System for Finish Work, especially for dwelling apartment building projects. The first step of modeling in this research is case study.

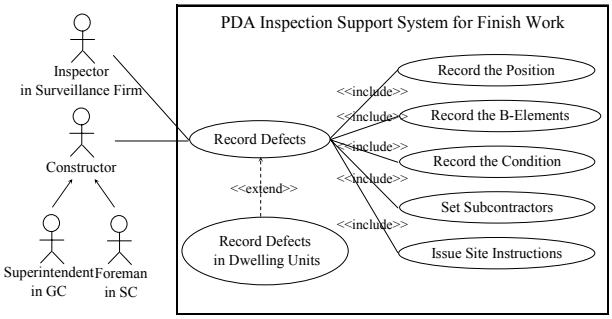

Figure 2 Use Case Diagram

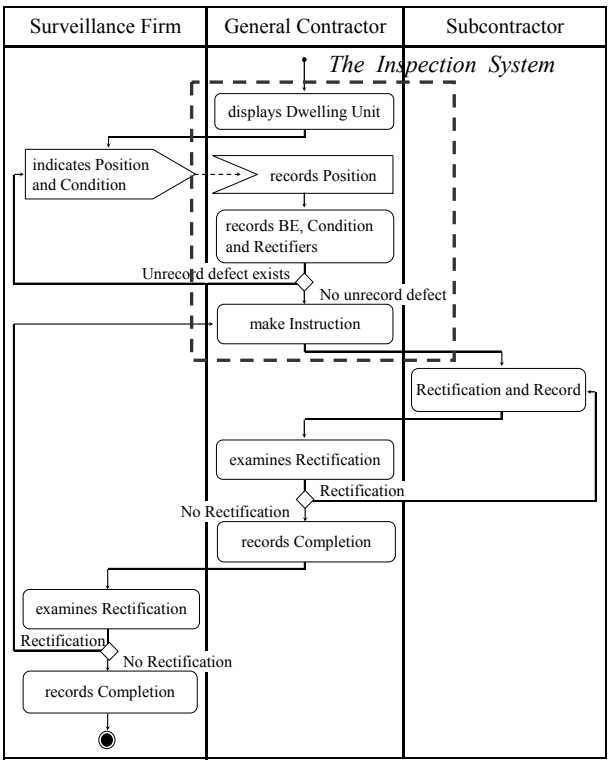

Figure 4 Activity Diagram

3.1 Use Case and Scenario

Figure 1 shows a use case diagram in the case. It shows that an inspector in surveillance firm, a superintendent in general contractor and a foreman in subcontractor can be the user of the PDA system. The inspection work with the system includes five subworks such as “record the position” and “issue site instruction”. It is extended from the work of “record defects in dwelling units.” The inspection for common corridor is possible as another use case.
Figure 2 shows a scenario in the case that an inspector in surveillance firm inspects dwelling units. In this scenario, a superintendent in general contractor uses the PDA system, and issues site instruction for the rectifying. A rectifier is a foreman in subcontractor.

3.2 Flow of Activity and Message

Figure 4 shows an activity diagram in the case.

Scenario

Name: Inspector in surveillance firm inspects the dwelling units.
Inspector = Surveillance Firm, Observer = GC, Rectifier = SC
System = PDA Inspection Support System for Finish Work
1) Observer displays the drawing of the dwelling unit with System.
2) Inspector indicates the position and condition of the defect.
3) Observer records the position with System.
4) Observer records the building-elements, the condition the subcontractors to rectify the defect with System.
5) Oberber make site instructions with System and issue it.
6) Rectifier rectifies the defect and record the completion.
7) Observer examines the rectification and reports it to Inspector.
8) Inspector examines the rectification and records the completion.

Figure 3 Scenario

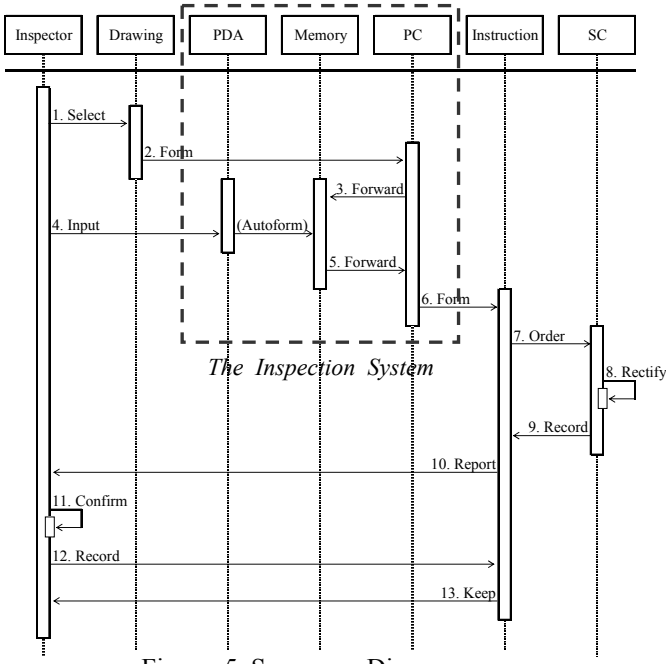

Figure 5 Sequence Diagram

It basically indicates a flowchart in the case. The flow and sequence of works make clear. It also sets the lane for affiliates. Each role makes clear in the inspection. Moreover, it can express the decision when guard conditions are used to indicate different possible transitions that depend on Boolean conditions [7]. Works can be classified by the type of content such as decision making and data input. This classification is related to the scope and role of computer-aided systematization.

Figure 5 shows a sequence diagram in the case. It focuses on the message flow. The related subjects are the sender and the receiver on messages. They include engineers such as inspector, and constituents of the system such as PDA. This diagram is also related to the scope and role of computer-aided systematization.

3.3 Design Pattern in GUI

The authors recognize GUI as the important object of design pattern for EUC. It is familiar to both end users and system developers. The left sequence diagram in Figure 6 shows message flow around a core of GUI model in the case. This GUI model, which the authors have arranged for EUC, has five properties. The first one is the name such as pattern-A and pattern-B, which is just for the identification. The second one is the type of control such as list and scrollbar. In this case, this means a tool in data input. The third one is the type of access to GUI such as the selection of item and the direct input of information. The forth one is the type of data such as Integer, String and Boolean. The fifth one is the number of data input.

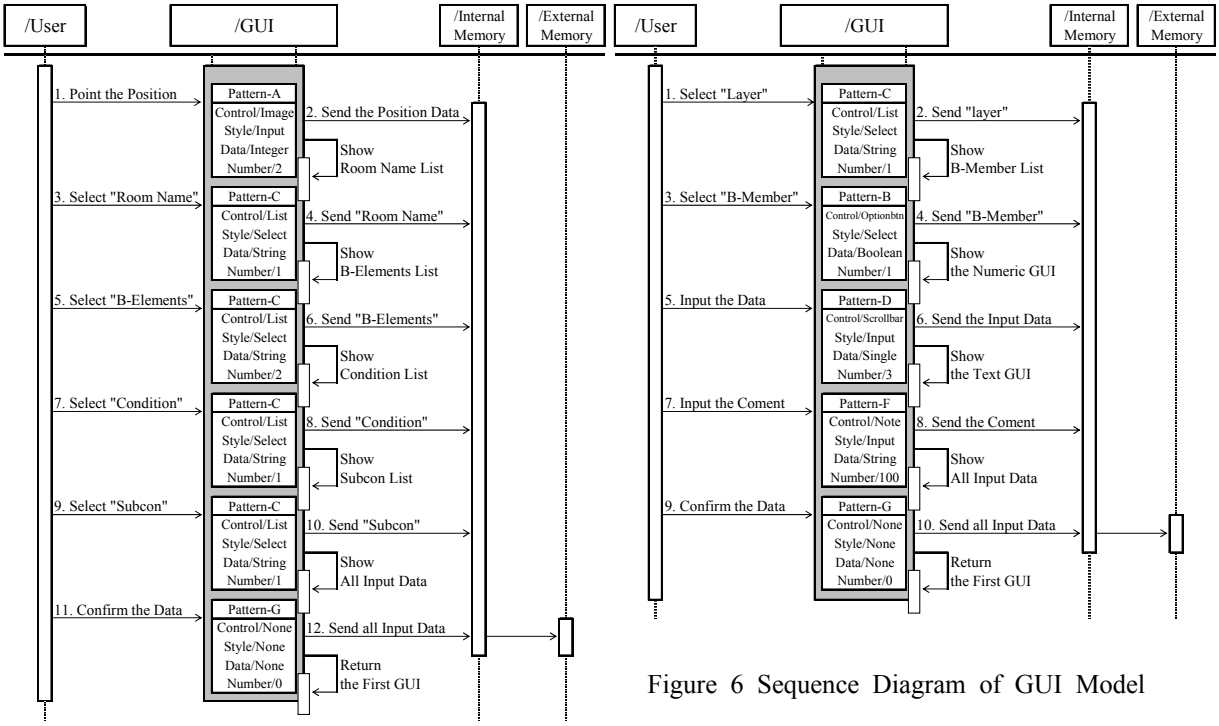

Figure 6 Sequence Diagram of GUI Model

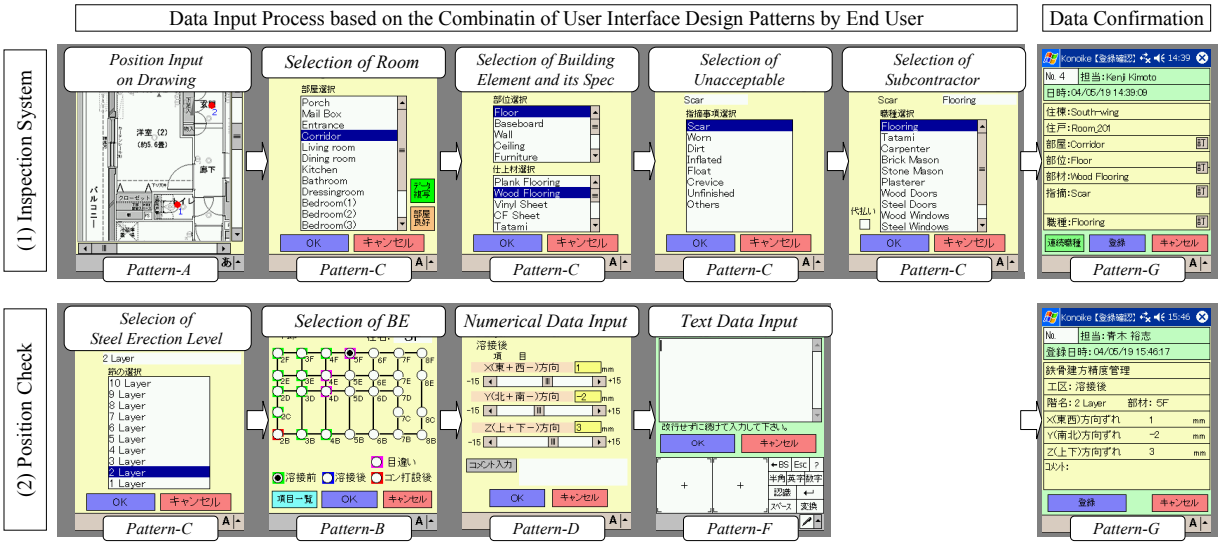

Figure 7 Development of GUI by GUI model

The type of control and that of access are related to that of data. For instance, the selection from the list is suitable for the input of the item. The use of scrollbar is suitable for the input of numerical data, especially by users with gloves out of doors. This is possible in construction site. As sequence diagram shows message flow, the input and output in the system makes clear. The content of this GUI model is also familiar to both end users and system developers. Therefore, this flow can be designed by the collaboration of end users and system developers.

The right one in Figure 6 shows the case of Position Monitoring System with PDA. This case uses the right control such as list, option button and scrollbar, in the right place. Once the sequence diagram of GUI model is established, the development of actual GUI is easy and doesn't need much time. Figure 7 shows the development of actual GUI in the system. The upper flow of GUI shows the case of Inspection System. The lower one shows that of Position Monitoring System. These cases well express the feature of data input in PDA systems.

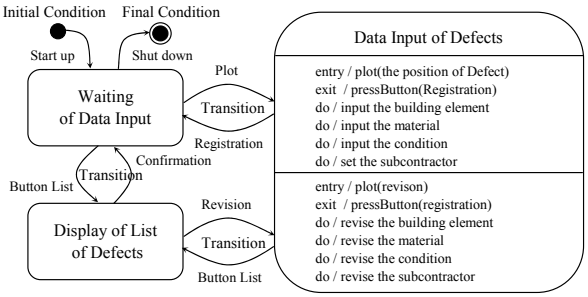

Figure 8 Statechart Diagram

3.4 State Transition in GUI

Actual use of the system is the process of not sequential, but trial and error. Users will go ahead and back in the process. The system must correspond to this situation. Figure 8 shows the statechart diagram of GUI in the case. Basic states are three: the waiting state of data input, the inputting state of data, and the reading state of list. This diagram can be a users' manual and specification for the development. Figure 6 and 8 are complementary each other.

3.5 Improvement of System

The UML is a graphical language for visualizing, specifying, constructing, and documenting the artifacts of a software-intensive system [7]. Therefore, it can express the difference among systems visually. There is some possibility of expressing the effect of the introduction of system, and that of the improvement of one. Figure 9 shows sequence diagrams of three models about the inspection work. Model 1 is the traditional way with paper sheets for both the data input and the rectifying order. Model 2 uses the PDA system for the data input, and paper sheets for the order. Model 3 uses the PDA system and the network for both the data input and the order. The work volume of GC decreases at the transition from Model 1 to Model 2. To make clear the effect, the authors divide a model to two domains: man area and machine one, and classify information to two domains: analog information and digital one. Through the improvement, machine area increases and is refined. The information is digitized.

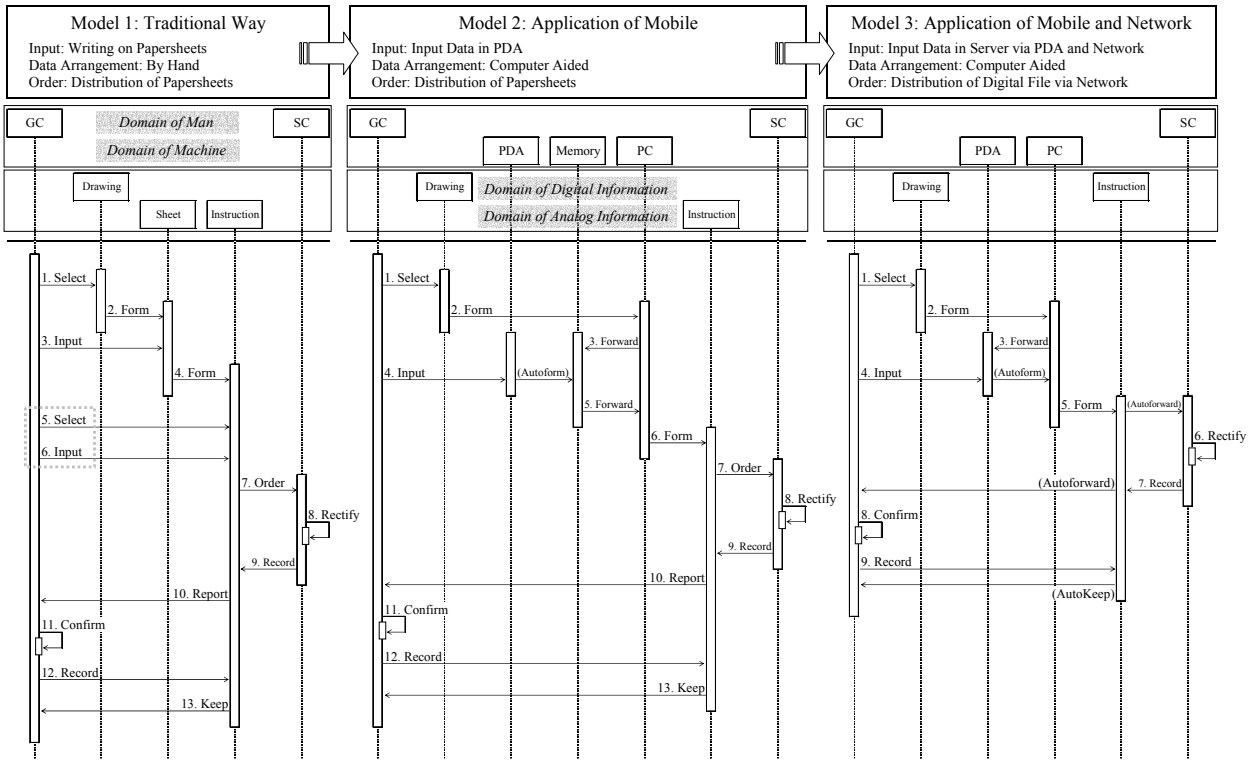

Figure 9 Comparison of Model by Sequence Diagram

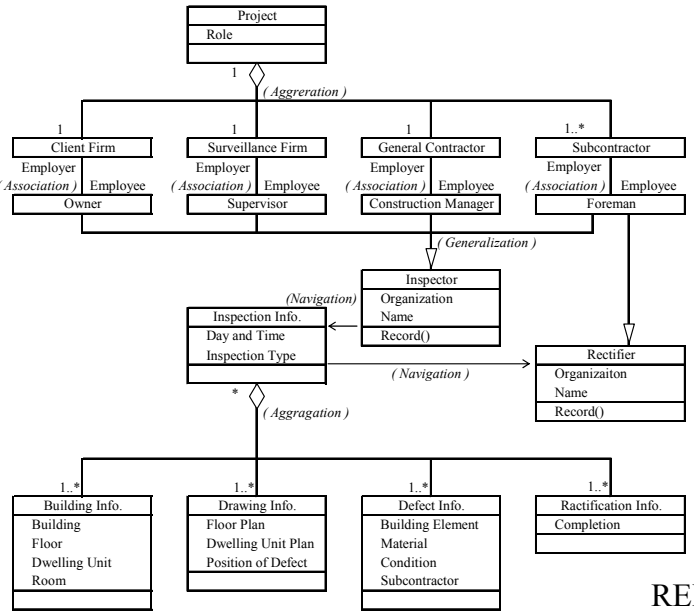

Figure 10 Class Diagram

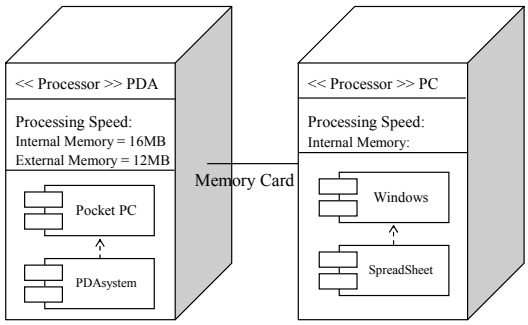

Figure 11 Deployment Diagram

3.6 Static System Structure

Figure 10 shows a class diagram in the case. A class diagram is a graph of classifier elements connected by their various static relationships [7]. The diagram shows the structure of elements including the relation among the elements. Defect information is composed of building information, drawing information, defect information, and rectification information.
Figure 11 shows a deployment diagram in the case. Processors are PDA and PC. It also expresses component diagram. Software in both processors depends on operating systems.

4. SUMMARY AND CONCLUSION

This paper describes the methodology of the development of mobile computing system based on EUC. The authors see the advantages of design pattern of user interface as the mechanism to acquire the flexibility of system. Moreover, they see that of UML as the communication tool not only between end users and system developers but also among system developers.
The paper introduces the description of the development process of PDA system with UML. Sequential diagram of GUI model well expresses the feature and design pattern of user interface. End users can take part in the design, and system developers can execute the coding of real system with it. That is, it works as modeling based on EUC. Moreover, the comparison between models with sequential diagram well expresses the effect of the introduction of computer-aided system, and that of the improvement of one. Other diagrams in UML also express the model from various kinds of viewpoints that are useful for the development of system.

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INTEGRATION OF AUTOMATED DATA COLLECTION TECHNOLOGIES FOR REAL-TIME FIELD MATERIALS MANAGEMENT

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Abstract: This paper describes a research study that is investigating data and technology requirements for the implementation of integrated real-time materials management on construction job sites. Specifically, the research aims (1) to formalize methods for accurate and timely materials tracking and (2) to define data integration needs between sensing technologies, materials management, and project control systems. The first phase of this study focused on materials locating technologies. Preliminary results from field trials conducted as part of the first phase of this project are presented.

Keywords: materials management, information technology, sensing, computer integrated construction

1 INTRODUCTION

Materials management, the process for planning and controlling all the necessary efforts to ensure that the right quality and quantity of materials are specified in a timely manner, obtained at reasonable cost, and used when needed [1], plays a major role in the construction industry. Materials management stands also for an essential project's control tool that when merged with engineering tries to reach both cost objectives and project needs [2]. In a typical construction project, materials account for 40-50% of its total cost. According to the 1997 U.S. Economic Census, the materials, components, supplies, and their management services for residential and industrial buildings, heavy construction, and infrastructure projects cost $124 billions [3]. Materials management is also recognized as one of the industry's best practices by both the Construction Industry Institute (CII) and the European Construction Institute (ECI).

While materials management has been largely analyzed, its materials handling procedures on construction job sites, known as field materials management, remain almost unexploited. Contractors' planning effort in materials handling operations is extremely limited [4]. According to a CII study, materials' availability on construction job sites increases 6% craft labor productivity in industrial projects, while the implementation of computerized support systems provides an additional gain between 4 and 6% [5]. Measurement of inefficiencies related to on-site materials handling operations confirms the potential for improving materials management on construction job sites.

Current field materials management processes are error prone and significantly decrease productivity. Locating and identifying materials on construction job sites consume excessive amounts of working time and labor effort, negatively acting on the construction success indicators of safety, schedule, and cost. In a study developed by O'Brien, the time spent on handling materials and preparatory operations by electrical workers was as much as 42%, while devoting only 32% of their working time to productive tasks [4]. Bell and Stukhart stated that foremen lost 20% of their working time hunting for resources, while leaving the crews unsupervised and hence cutting productivity down [6]. According to the same authors, the availability of materials to begin an activity affects craft labor productivity by decreasing the number of repetitive site trips, and increasing the associated amount of time spent. On power plant construction sites, Borcherding observed that 27.7% of the craft worker's time was idle or non-productive due to the unavailability of the correct materials and tools at the right time [7]. Significant competitive advantages would come through new technology devices to automatically control and update materials' information and status on construction job sites. For instance, automatic, reliable, and instant location of the on-site components belonging to critical activities would result in a confident and timely planning of the execution of those activities, and therefore minimize the risks of incurring project delays.

A recent Construction Industry Institute (CII) study identified field materials management as the area that company managements thought had both the greatest potential for improvement and the greatest positive development impact on engineering construction work processes [8]. According to 82% of the surveyed construction organizations, field materials management practices would be significantly improved by the introduction of technology, while 85% of those organizations agreed that technology devices would have a clear and positive impact

within those practices. The knowledge of accurate and timely-identified construction materials is important for project success.

New technology and sensing devices can greatly enhance field materials management. Precise tracking, finding, and distributing of the correct materials at the right time would highly increase craft labor productivity, reduce labor idle-time and the number of repetitive site trips, and hence improve safety performance. Additionally, the overall number of work disruptions due to material unavailability would be reduced, creating a clear and positive benefit to cost ratio within the construction industry that would accelerate the deployment and implementation of new technology and sensing devices.

2 BACKGROUND AND SIGNIFICANCE OF FIELD MATERIALS MANAGEMENT

Manufacturing materials management has been extensively studied and successfully applied for decades. Inventory management, materials-requirements-planning, and just-in-time delivery are the standard techniques for different demand environments, which are usually characterized by their levels of continuity, uniformity and dependency [9]. Within manufacturing, these demand characteristics are the most influential factors in determining the adequacy of a particular formal approach to materials management.

Materials management within construction resembles that of manufacturing only at a conceptual level [9]. Objectives, inputs, activities, and outputs are some of the conceptual parallelisms between manufacturing and construction materials management. However, unique and dynamic characteristics of construction environments, in conjunction with inaccurate or incomplete project data input, cause a lack of systematic methods to fulfill construction materials management principles and objectives.

Materials management needs to be understood as an integrated construction management process among all project stages. The harmonization and coordination of materials by the adequate methods and tools is necessary for business planning, preliminary design, final design, procurement, vendor control, construction, and project closeout. During the business planning phase, a materials manager is usually designated to report directly to the project manager, and a materials focus is clearly set in the project's mission statement. In the preliminary design phase, managers define materials' basic specifications while trying to minimize the design effort. As the final design goes on, the project team uses the generated information to prepare drawings and detailed specifications for materials' procurement. In the procurement phase, those specifications and long term factors, such as maintenance and operational costs, determine the best value for the price of each procured item. During vendor control, materials managers focus on avoiding changes in the specifications of the ordered materials, and on controlling their fabrication and delivery status. While constructing, the main focus is placed on field operations, with the goal of tracking, finding, and distributing the right material at the correct location at the precise time. Finally, the project closeout disposes of the surplus materials, while an analysis of the employed system generates future improvements and suggestions.

Successful approaches to manage construction materials possess intrinsic qualities and characteristics. Early planning, top management support and site training programs established early in the project are some of the basic attributes for a correct materials policy [10]. Additionally, the implementation of interconnected communication mechanisms among the different construction players is a condition for an effective management of construction materials. The presence of communication channels among the owner, the contractor, project managers, and the job site strengthen the correct flow of materials' information in a precise sequence.

The existence of a materials management system enhances this interconnectivity by sharing a common database, therefore eliminating redundant input while minimizing data storage. Its use further increases data accuracy, productivity and data-flow, and enables potential access to materials' real-time information. However, management systems need to be populated with the appropriate data.

Recent research initiatives explored the use of new technologies and sensing devices to collect materials' status on construction job sites in a timely manner. An early approach by Jaselskis et al. proposed radio frequency identification devices (RFID) for tracking high valued materials on construction job sites [11]. In a study implemented by Cheng and Chen, barcodes and geographic information systems (GIS) were the two basic components of an automated schedule monitoring system to control the erection of prefabricated concrete components [12]. Chen and Wong developed an incentive reward barcode-enabled program that encouraged on-site workers to decrease avoidable wastes [13]. Akinci et al. proposed radio frequency identification solutions for tracking precast concrete elements during their construction lifecycle, while keeping record of their as built information [14]. NIST conducts a research for establishing standards to support identification and tracking of construction components by means of different sensing technologies, such as barcodes, radio frequency identification devices, and global positioning systems (GPS) [15]. Finally, Stone et al. merged laser detection and ranging (LADAR's) with barcode technology in order to read the materials' identification labels at maximum distances between 30 and 40 meters [16].

Success from these research projects has opened the doors of automated data collection (ADC) technologies to manage materials on construction job sites. Combined with the latest versions in portable computers and wireless communications, ADC technologies may create the data stream for materials to move efficiently on construction job sites, substantially modifying current field materials management.

3 AUTOMATED DATA COLLECTION (ADC) TECHNOLOGIES FOR FIELD MATERIALS MANAGEMENT

ADC devices are continuously evolving and becoming common in industries such as manufacturing, logistics, and health care. Standard and off-the-shelf automated data collectors can be of great convenience on construction job sites, supporting automatic access to reliable real-time information of on-site materials.

3.1 Barcode technology

Barcode labels represent a read-only identifying technology extensively applied in manufacturing since 1970's. Barcode technology encloses the knowledge for encoding, printing, scanning, decoding, and verifying the symbols contained in labels. Electro-optical barcode scanners illuminate and read a symbol by measuring the reflected light's waveform; then, the measured signal is digitalized. This sensing system enables the identification of labeled items, requiring a clear line-of-sight between label and reader in maximum distances of inches.
While traditional one-dimensional codes have small storage capacities, two-dimensional encoding systems have highly increased them. Two-dimensional stacked and matrix codes act as a database, assuring a complete visualization of the labeled item by means of the stored information. Correction and error detection decoding techniques are a fundamental part of these expanded systems.
Even though barcode's low-costs and off-the-shelf solutions can accelerate its deployment within the construction industry, the need for a clear line-of-sight with short read ranges and the finite lifetime of the labels under harsh environments limit its applications on construction job sites.

3.2 Contact memory buttons

Contact memory buttons stands for a read/write technology for use in extreme environments. The hermetically sealed buttons are capable to resist severe temperatures, shocks, vibrations, radiations, and maintenance in aggressive solvents and salty waters. However, the technology requires direct contact between the memory device and a button link connected to a portable computer to read or update the information in the button. Maximum commercial storage capacities range up to 8 Mb.
Contact memory buttons are a growing technology with multiple applications in severe environments, such as that of the U.S. Department of Defense, and those of the oil, railroads and manufacturing industries.

3.3 Radio Frequency Identification Devices (RFID)

RFID is a wireless read/write identification system that emerged in the 80's. RFID provides for sending and receiving data via radio signals with non-contact and non-line-of-sight between components, even under hostile environments. An RFID system is composed by three components, antennas or metal coils, transceivers, and transponders (tags). Usually antenna and transceiver are mounted together to become a reader. When a tag's antenna detects a radio signal from a receiver, it replies back to the receiver sending the encoded information.
Transponders are classified as either active or passive. On the one hand, passive tags operate with the energy of the signal transmitted by the reader and usually are read-only devices, acting for identification purposes. On the other hand, active tags are powered by an internal battery and are read/write. The trade off between them is that active tags have larger memories (up to a few Mb) and longer read ranges (up to a maximum of 100 feet), while passive tags are lighter, smaller and more economical.
The promises of growth of the technology that would enhance performances and reduce costs, together with its non-contact and non-line of sight nature, would make RFID an ideal technology for locating and tracking materials on construction job sites.

3.4 Smart labels

Smart labels stand for a simplified and inexpensive version of RFID tags. Working with similar radio frequency principles, smart labels operate with a silicon microprocessor that connects printed carbon-ink electrodes (instead of the tag's metal coil) on the reverse of a paper label.
Although the resulting price (usually less than $0.5) and the physical flexibility of the tags may be attractive for the construction industry, their extremely limited read ranges and low memory keep them away from construction job sites.

3.5 Global Positioning System (GPS)

GPS is an outdoor satellite-based worldwide radio-navigation system formed by a constellation of 24 satellites, ground control stations, and end users. GPS uses triangulation from these satellites in order to determine a three dimensional position. To triangulate, a GPS receiver needs to compute the

distances to at least four different satellites at any given time. Distances to the receiver are computed measuring the travel time of radio signals from each one of these four satellites. Atmosphere conditions and satellites' location above the receiver influence the resulting position and its accuracy.
By default, any computed position has an intrinsic maximum error of 45 feet (raw data). However, differential GPS (DGPS) decreases the error of the raw data using a fixed receiver whose position must be previously known. Ground base stations, coastguard beacons, WAAS, and OmniSTAR receivers reduce the error to less than 10 feet, while real-time kinematic GPS (RTK GPS) minimizes the position's error to less than one centimeter in a few miles radius around a separate base station, having a trade off in highly increased costs.
GPS is an established location technology that offers a wide range of off-the-shelf solutions in both hardware and software. Although GPS applications are not uncommon in construction practices, such as positioning of equipment and surveying, its potential to improve the management of materials on construction job sites remains unexplored.

3.6 Laser scanners

A laser scanner is a range finder with a spherical sensor device that measures distances to the surrounding objects. A diode laser emits a pulse of light that, when colliding with an object, partially reflects back to the range finder. A direct comparison of the phases of the emitted and returned signal determines the distance to the object. The output signal is in the form of consecutive scan lines. The effective depth of field of a laser scanner normally ranges between 3 and 300 feet.
Even though laser scanners would deliver highly accurate visual information of a construction scene, the tremendous computational effort to transform the raw visual data into meaningful information, the inability of the technology to see through objects, and the relatively slow scans have focused this technology for solving other civil engineering problems.

3.7 Laser Detection And Ranging (LADAR)

LADARs are another variant of laser range finders. A photomultiplier processes the returned photons of an emitted light pulse and simultaneously obtains the time-off-flight range distances to the impacted objects. The output signal is a visualization of the objects in front of the LADAR in terms of distances.
When compared with laser scanners, LADARs have a poor horizontal and vertical coverage, and a short depth of field. However, LADARs have lower costs and provide for close real-time visual information.
At the present time, the unavoidable presence of obstacles in dynamic construction environments, the need for post-processing the raw visual data, and the experimenting stage of the technology slow down the introduction of LADARs on construction job sites.

3.8 Webcams

Webcams can provide real-time visual information of construction job sites. Even though their application can be clearly profitable in some construction applications due to commercial availability and low costs, the high post-processing efforts of the collected data to identify, track and locate materials make their use impractical for tasks that require some expertise.

3.9 Portable computers

Mobile and wearable computers offer a convenient way to collect, access, and store real-time data on construction job sites. Personnel digital assistants, handheld computers, rugged laptop computers, and touch-screen computers come usually equipped with wireless communication hardware and software, becoming effective tools to overcome traditional, time consuming, and unreliable paper work. However, portable computers as automated data collectors rely on human-data entry. Other potential technologies discussed in this paper are better suit for the data gathering process.

4 CASE STUDY

FIATECH (Fully Integrated and Automated Technology), an industry consortium focused on research, development, and deployment of technologies within capital projects and facilities, has an ongoing project, called Smart Chips, that aims to investigate the use of sensing technologies in construction job sites. One of the pilot studies conducted by the Smart Chips project team is presented here.

4.1 Project description

The project applied GPS technology to improve the process of locating pipe spools in lay down yards of large industrial projects. FIATECH, the Smart Chips project, Kellogg Brown and Root (KBR), British Petroleum (BP), Trimble, Data Scan, Geo Spatial Innovations (GSI), and the University of Texas at Austin were the key project participants.

4.2 Objectives

The goals of this study were to quantify the potential benefits derived from the integration of GPS within materials locating processes and to evaluate its technical feasibility, assessing in its limitations and providing recommendations for further

improvements. Lay down yards were the preferred scenario for measuring those potential benefits.

4.3 Technology used

To achieve these objectives, the selected locating technologies were integrated with current materials management systems. Accurate and smooth integration of field materials management processes, new technology devices, database management systems, and data transformation/transmission were the backbone of this study.

4.3.1 GPS System

Trimble's GPS Pathfinder Power determined its own location at any given time. The GPS reader was a combination of differential GPS (DGPS) receiver and antenna. Position was defined in terms of three coordinates (X, Y, and Z). The backpack mounted device (Figure 1) enabled a real-time sub-meter accuracy using OmniSTAR DGPS correction.

Figure 1. GPS antenna and receiver

4.3.2 Handheld device and software

The handheld computer PDT 8100 was a rugged data-collection device. The computer was wired to the GPS receiver in order to enable the collection of measured positions. PDT 8100 incorporated key data entry option and sealed joints to withstand construction environment's demands. A ¼ VGA display touchable screen allowed the end user to interact with software packages.
GSI's Pocket Collector software had two main functions. First, it operated as the interface between the end user and the GPS receiver. Second, Pocket Collector integrated the GPS position-based functions of navigation, tracking, timing, and mapping (Figure 2).

4.4 Preliminary results

Thus far, the research team has accomplished the first two steps of the project. In the first step, the team selected the appropriate technology devices and integrated them with current locating methods. In the second step, the team performed a field trial to verify the feasibility of the GPS technology to locate materials.

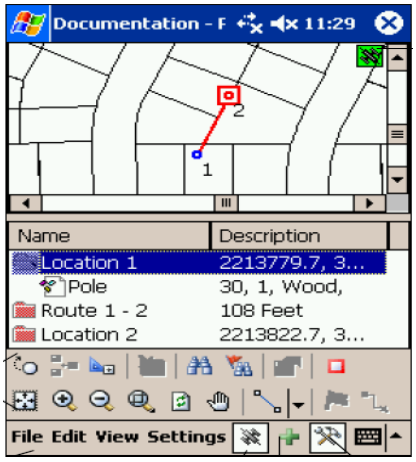

Figure 2. Positions of both targeted pipe spool and user could be visualized

4.5 Field trial

The field trial was designed to analyze the technical feasibility of the GPS technology for locating materials. The field trial consisted in finding 20 components that had been previously tagged with a barcode label, and their positions recorded in the handheld computer. The GPS navigation and mapping functions were the basis of the user search. Once the user learned how to manage the handheld device and software, all the items were successfully identified and located. The sub-meter accuracy was required to locate a particular item in crowded areas (Figure 3).

Figure 3. Crowded areas require sub-meter accuracy

4.6 Potential benefits and identified barriers

The experience acquired during the field trial encouraged us to share some of the observations regarding the technical feasibility, limitations, and potential benefits of the GPS integration within field materials management, including:
(1) Merging GPS within traditional practices would only result in partial benefits, while re-engineering current locating processes around GPS has the potential to further improve schedule, reliability and productivity.
(2) Even though GPS technology automatically determined accurate materials' positions in lay down yards with thousands of stored components, the identification of pipe spools still relied on human data entry. Application of isometric drawings, barcodes, and RFIDs would further reduce the percentage of errors during the data collection process.
(3) The knowledge of the components' location in large lay down yards opens the possibility to pre-determine routes and pickup sequences for tasks such as materials loading.
(4) Sub-meter accuracy is required when locating materials in crowded areas.
The research team is conducting more field tests to clearly measure and quantify the impact of GPS within materials locating processes, while enhancing the assessment for recommendations and identified barriers.

Acknowledgments

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A Project Progress Measurement and Management System

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Abstract: A progress management in construction projects plays an important role in providing as-built information for project planning, control, cost engineering, and many others. However, progress information has not been collected through objective methods or criteria but mainly based on an individual's own experience or subjective judgment, which results in the limits of consistency, objectiveness, and accuracy in the progress management. This research aims at proposing a progress measurement framework that allows managing and applying various measurement methods dependent on work items to overcome the problems and limits of the current progress management. The framework was developed with a focus on integration of work breakdown structure, cost breakdown structure, and progress measurement methods, and it consists of three main objects: work, activity, and progress measurement unit. Base on the framework, an information system named PROSYS (project PRogress management SYStem) was developed to generate activities and progress measurement units depending on the characteristics of projects and work items, and to keep track of project progress more efficiently and effectively.

Keywords: Progress management, Progress measurement, Information system

1. INTRODUCTION

Project management information systems are increasingly applied at construction projects for more efficient management by collecting as-built information and supporting decision-making. Among the various types of as-built information, the project progress rate is one of the critical indices that represent the project performance and progress state, and it helps timely and accurate decision-makings by providing basic information that can be applied to project planning and control as well as cost engineering. However, the project progress management has not been quite effective, since it has not been based on objective data or criteria, but based on subjective judgments and different criteria dependent on an individual's experiences or preferences [1].

Regarding research on the progress management, Thomas and Mathews [2] classified the progress management into three categories by the progress measurement method, which are estimated percent complete, physical progress measurement, and earned value. CII [3] and Flemming and Koppleman [4] classified the measurement methods at more detailed level, and suggested the use of a different method depending on the work item or project condition. However, there has been lack of a framework for applying various measurement methods with considering a work item and project characteristics based on objective and consistent criteria. In most construction projects, measurement methods are used inconsistently project by project without objective criteria, which make it more difficult to accumulate and reuse invaluable as-built information.

The objective of this research is to develop a progress measurement framework, which supports to apply various methods with considering a work item and project characteristics based on objective and consistent criteria. To do so, it was analyzed what kind of measurement methods exist, and how they could be applied differently depending on the characteristics of a work item and a project. Based on the methods, a progress measurement framework was developed to provide various measurement methods, depending on work items and project characteristics. Finally, based on the proposed framework, an information system called PROSYS (project PRogress management SYStem) was developed.

2. PROGRESS MANAGEMENT IN CONSTRUCTION PROJECTS

The definition of the progress management, measurement methods, and their targets were studied through literature review. And they are discussed in the following sections.

2.1 Definition of Progress Management

Generally, the progress management is defined differently depending on the aspects of cost engineering and scheduling, respectively [5]. However, in overall view, the progress management can be considered as the integration of cost and schedule [1]. Base on this definition, the progress management in this paper is the measurement and analysis of degree of progress based on measurement quantity as well as its budget, which is the same as budgeted cost work performed (BCWP) of Cost/Schedule Control Systems (C/SCS) [6].

2.2 Progress Measurement Methods and Targets

Existing research on progress management, listed in Table 1, suggested various measurement methods and targets in progress management. Measurement methods can be categorized into measuring, estimating, and checking, while targets can be classified into work quantity, milestone, process, and time.

Besides Eldin [7] developed a computer application for the measurement of work progress based on weighted milestones and earned value, and Choi [8] insisted that the effectiveness and efficiency of measuring progress can be maximized through specifying major items that can represent the real work progress.

Although the existing research suggested various measurement methods for work progress, the progress management has not been based on objective criteria but based on the manager's judgments and conveniences. In addition, the consistency and accuracy of work progress can be improved through application of various measurement methods and breakdown of measurement targets at more detailed level, however, this would require tremendous time and efforts to build criteria and to collect data in each project. To the contrary, estimating work progress would reduce the accuracy and consistency, although it does not need time and efforts that much. Therefore, there is a tradeoff relationship between accuracy/consistency and efficiency in progress management [1]

Accordingly, it would be very efficient to build a computerized system that allows various choices for progress measurement dependent on the degree of impact of a work for better accuracy and timeliness in progress management. To do so, a framework needs to be developed to suggest and manage criteria, such as measuring methods, targets, and rules, and to apply them flexibly by work items and project characteristics in a consistent and timely manner.

Table 1 Measurement Methods and Targets

Research	Measurement Method	Measurement Target
Thomas & Mathews [2]	Estimated percent complete	Progress state (Individual evaluation)
	Physical progress measurement	Installed quantity
	Earned value	Measurable level of work progress
CII [3]	Unit completed	Installed quantity
	Incremental milestone,	Milestone
	Start/finish, supervisor	Start /finish point of work
	Opinion	Progress state
	Cost ratio	None
	Weighted or equivalent units	Finish point or progress state of work
Fleming & Koppleman [4]	Weighted milestones	Finish point of weighted milestone
	Fixed formula by task	Finish point of work (0-100) or Start /finish point of work (50-50)
	Percent complete & milestones gates	Progress state based on milestone
	Earned standards	None
	Apportioned relationships to discrete work	None
	Level of effort	Time of work

3. PROGRESS MEASUREMENT METHODS

Based the measurement methods listed in Table 1, only the methods that have measurement targets were selected and reaggranged by excluding redundancy and ambiguity in its contents. The reaggranged methods were reviewed through the analysis on existing office construction projects and workshops with construction practitioners in Samsung Corporation. Finally, possible methods in each work item were derived for a typical office project.

3.1 Derivation of Progress Measurement Methods

The progress measurement methods by work items were derived in the following manner. First, based on the existing research and paradigm at practice, 3 measurement methods and 6 measurement targets were derived. 3 measurement methods are physical measurement, milestone measurement, and estimated percent completed, and 6 measurement targets are quantities of a single major work item, multiple major work items and all work items, milestone, start/finish point, and percent completed. Secondly, 18 types of measurement methods were generated by

simply combining 3 methods and 6 targets, and they were narrowed down into 6 measurement methods through brainstorming with construction practitioners with considering applicability and redundancy of the candidate methods. The final 6 measurement methods are listed along with examples in Table 2.

3.2 Criteria for Applying Measurement Methods

For more accurate progress management, it is necessary to apply various measurement methods with considering the characteristics of a work item and a project, and objective criteria are essential in this process. Therefore, this research adopted three factors affecting progress measurement accuracy proposed by Jung et al. [9] as criteria to choose an appropriate measurement method for a work item. Those factors are budget weight of a work item, typical durations of activities for a work item and the degree of ease in determining accurate progress rate in each activity. Based on these factors, criteria for applying measurement methods are developed on the assumption that the project progress is measured at the activity level every week.

Table 2. Measurement Methods & Examples

Measurement				Examples						
Measurement Methods		Criteria	Target	Work	Budget items					Checkpoint
					No.	Description	Standard	Unit	Budget rate (%)	
1	Measure installed quantity of a single major item	Activities of this work item take more than a week, and budget rate is relatively high. A single major budget item can represent the work progress.	Single major budget item	Form	1	Wood form	3 Times	m^2	4.0555	Installed quantity of No. 1 item
					2	Wood form	4 Times	m^2	0.1104	
					3	Wood form	Round shape	m^2	0.0424	
2	Measure installed quantities of multiple major items	Activities of this work item take more than a week, and budget rate is relatively high. Multiple major budget items can represent the work progress.	Multiple major budget items	Interior decoration tile	1	Ceramic tile for wall	200mm *200mm	m^2	0.0241	Installed quantity of No. 5&6 items
					…	…	…	…	…	
					5	Tile for wall	150 mm *150 mm	m^2	0.1010	
					6	Tile for floor	150 mm *150 mm	m^2	0.0554	
					…	…	…	…	…	
3	Measure installed quantities of all items	Activities of this work item require intensive monitoring or large influence over a project. A few budget items are assigned.	All budget items	Gutter & downspouts	1	Steel downspouts	D100	m	0.0077	Installed quantity of all items
					2	Steel downspouts	D150	m	0.0002	
					3	Floor drain	D100	EA	0.0027	
					4	Floor drain	D150, ME Room	EA	0.0010	
					5	Roof drain	D150	EA	0.0018	
4	Check start/finish of works	Activities of this work item take less than a week, and budget rate is relatively low. Activities progress can be measured by 0/100 % basis, which means that progress rate is 0% until the activity is finished.	Finish of work	Handrail	1	ST'L Handrail	D=50 H=900	m	0.0021	Start [0%]
					2	Heliport Handrail	D=50.8*4 H=1000	m	0.0401	
					3	Cooling-Tower Handrail	D=100*3 H=900	m	0.0270	Finish [100%]
					4	Rooftop Handrail	D=50.8 H=800	m	0.0784	
5	Check milestones	Activities of this work take more than a week, and milestones can be assigned in each activity. And different weights can be assigned in each milestone.	Milestones	Aluminum door/ window installation	1	FSD01	750* 2100	EA	0.0052	Finish frame installation [30%]
					…	…	…	…	…	
					4	FSD47	1900* 2100	EA	0.0011	Finish door installation [70%]
					…	…	…	…	…	
					8	SD51	1000* 2100	EA	0.0003	
6	Estimate percent complete	Activities have very long durations and its influence is very small. Activities do not have clear targets to measure for work progress. The progress can be determined by time or progress rate(s) of other works.	None	Usually indirect cost item is included in this category. However, this method is not recommended for measuring work progress.						

4. A PROGRESS MEASUREMENT FRAMEWORK

This research propose a progress measurement framework (PMF) based on measurement methods and criteria described in the previous section.
PMF has a three-dimensional structure that integrates work breakdown structure (WBS), cost break down structure (CBS), and measurement, and makes three main objects for progress measurement: work, activity, and progress measurement unit (PMU) as shown in Figure 1.

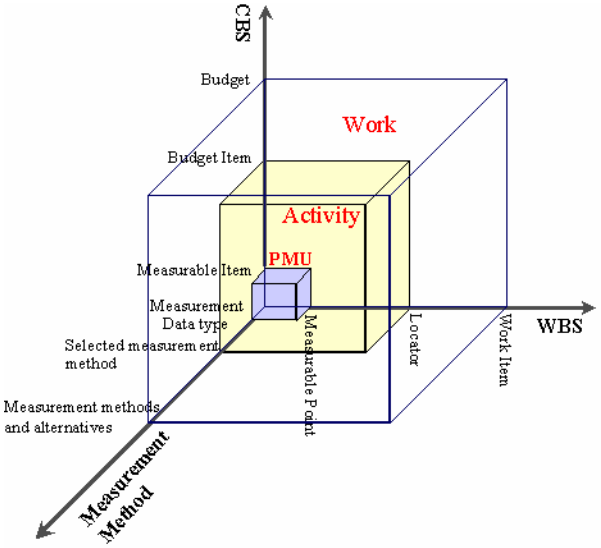

Figure 1. Progress Measurement Framework

WBS defines the structure for activities based on work item, locator, and measurement point. That is, each work item is divided into activities by locations where the work occurs, and activities have one or more measurement points for work progress.
CBS, which is for cost engineering, consists of three factors of budget, budget items, and measurable items. The structure of CBS can be almost identical to WBS at the high level, but CBS usually has the different level of detail from that of WBS. Therefore, in many cases, budget items of a cost account need to be reassigned into activities, and measurable items should be designated among the assigned budget items.

Measurement consists of alternative measurement methods, selected measurement method, and measurement data type. For a given work item, alternative measurement methods are available for progress management; an appropriate measurement method is selected for the work item based on the project characteristics; and progress data is collected in the specified data type to determine the progress at the activity level.
Although WBS is defined as an integrated structure for schedule and cost control systems [10], WBS and CBS are usually managed separately in reality [11, 12], which requires reassignments of budget items in CBS into the corresponding activities in WBS. Therefore, PMF defines a work as an integrated object of cost and schedule. Each work has assigned budget items and many alternatives for progress measurement of the work item, while a work progress is determined in each activity by measuring PMUs through the selected measurement method.

Activity is a unit where a progress rate is determined. It is generated through flexible combination of a work item and locators, such as site, building, story, space, and element, depending on the characteristics of a project.

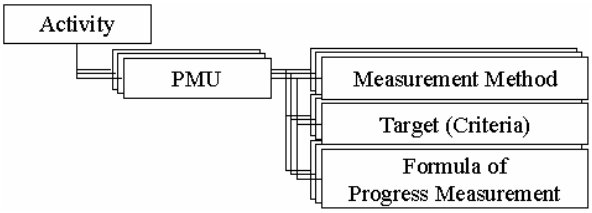

Figure 2. PMU's Structure

PMU, which is a unit to measure a work progress, tells what and how to measure progress for a specific work item, and it consists of measurement method, measurable item(s), and measurement point(s) as shown in Figure 2. An activity has one or more PMUs to measure targets, while a progress rate is determined in each activity through applying PMU values into the formula specified for the selected measurement method. Table 3 shows an example on how work, activity, and PMU are related and a work progress is determined. In addition, the overall project progress rate is determined by:

$$\text{Proj. Progress} = \frac{\sum (\text{Activity progress} \times \text{budget})}{\text{Project budget}} \times 100 \quad (1)$$

5. SYSTEM IMPLETMENTATION

An information system named PROSYS (project PRogress management SYStem) has been developed based on the progress measurement framework (PMF) described above. The objective of PROSYS is to support generation of activities and PMUs, integration of cost and activity by reassigning budget items into activities, measurement of work progress by utilizing PDAs, and analysis of work progress, etc. The system architecture and some of main features of PROSYS are presented in the following sections.

5.1 System Architecture & Information Flow

The system architecture of PROSYS is shown in Figure 3. PROSYS has two databases. One is a standard database that contains standard information, such as work items, measurement method and

Table 3. Examples of Work, Activity, and PMU

Work	Activity		PMU				Measurement		Activity progress rate	Project progress rate
	Name	Budget (won)	Msrmnt. Method	Target (unit)		Formula for work progress	Total quantity of target	Installed quantity		
Formwork	1F-formwork	47,000,000	[1]	Single major budget item (m^2)		$\frac{\text{Installed quantity}}{\text{Total quantity}} \times 100$	2690 (m^2)	1750 (m^2)	65.06 (%)	0.08 (%)
	2F-formwork	47,000,000	[1]	Single major budget item (m^2)		$\frac{\text{Installed quantity}}{\text{Total quantity}} \times 100$	2690 (m^2)	-	0(%)	0(%)
Door/ window installation	1F-door/window installation	111,644,500	[5]	Finish frame installation	30 (%)	∑ Weight of milestone	Finish frame installation	completed	100(%)	0.3 (%)
				Finish door/window installation	70 (%)		Finish door/window installation	completed		
	2F-door/window installation	111,644,500	[5]	Finish frame installation	30 (%)	∑ Weight of milestone	Finish frame installation	completed	30(%)	0.09 (%)
				Finish door/window installation	70 (%)		Finish door/window installation	-		

alternatives and typcial budget items for each work item and it is managed by standard manager. The other database is a project database managed by customization manager, and it manages project-specific information, such as the project schedule, activities, cost account and budget items, PMUs, etc. The progress measurement manager enables to measure progress based on generated PMUs, and it supports data collection through PDAs for more efficinet progress measurement. Accordingly, the information in PROSYS flows from standard manager to customization manager, and to progress measurement manager.

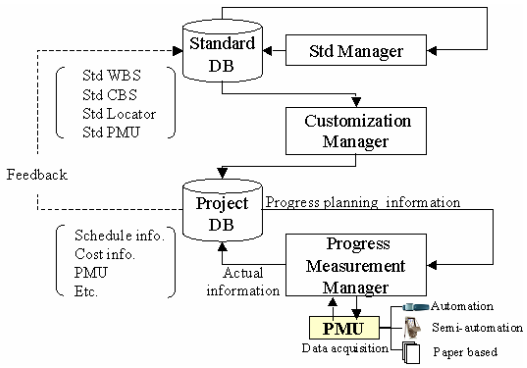

Figure 3. System Architecture

5.2 PROSYS

Some of main functions in PROSYS are presented in this section. Figure 4 shows the function to generate activities for a selected work item. A user selects locators, such as floor, space, and element, for the selected work item in the treeview of the left side of the window. And clicking generation button, in turn, generates activities shown at the bottom of the window in Figure 4.

Figure 5 shows the PMU generation. For the selected work item in the left side of the window, a standard measurement method and alternatives are shown, and the default value can be changed to fit to the project. A measurement method is determined at the work item level, since the system assumes the same measurement method is applied through the all activities that belong to the same work item. This is because of the management convinience. If different methods need to be applied, the work item can be divided into as many items as the number of measurement methods required.

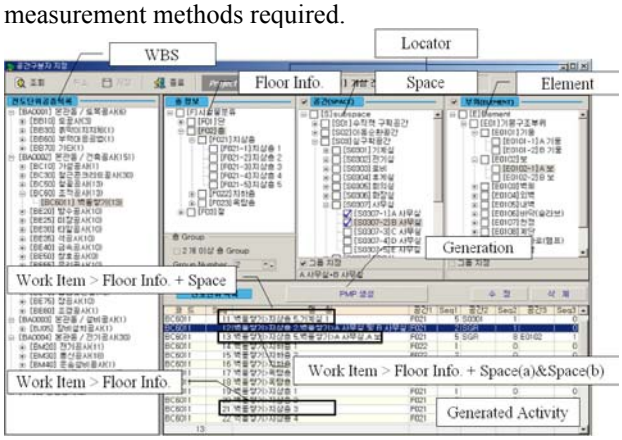

Figure 4. Activity Generation

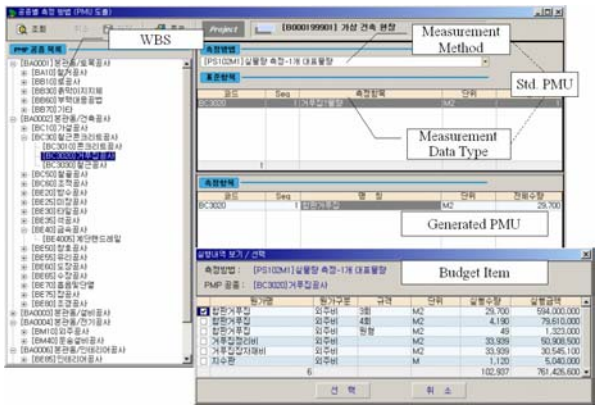

Figure 5. PMU Generation

Figure 6 shows the PDA module of PROSYS. After generating activities and PMUs, a work progress is measured through PMUs by using PDA. The left part of Figure 6 shows the inital page of PDA module, while the right part of Figure 6 shows the measurement window for a specific activity. A user measures progress according to the method specified at PMUs, and then the collected progress data is

summed and analyzed for project progress analysis as shown in Figure 7.

Figure 6. PDA Main & PMU measurement

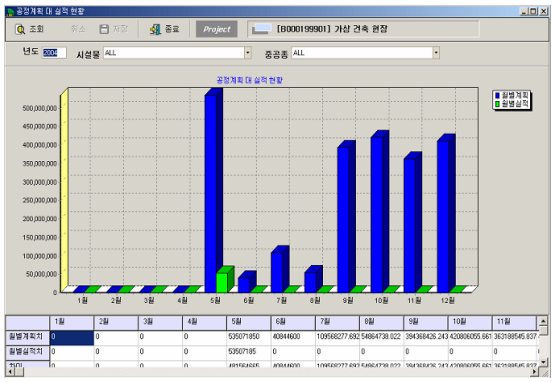

Figure 7. Monthly Progress Rate

6. CONCLUSIONS

This research proposed a progress measurement framework and developed an information system for more efficient and effective progress management based on the following outcomes:

1) six measurement methods were derived from the existing research [2, 3, 4, 7, 8],

2) the three-dimensional progress measurement framework were proposed on a basis of integrating WBS, CBS, and measurement methods,

3) the concept of progress measurement unit was proposed to measure a progress of an activity in a more consistent and objective manner,

4) an information system named PROSYS was developed to support the progress management based on the progress measurement framework.

The proposed progress measurement framework has been partially tested and validated by applying it to construction projects that had already been completed. In the near future, PROSYS will be fully tested for verification and validation of the progress measurement framework through an on-going construction project. Lessons-learned and experience will be shared through further publications.

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Wireless data acquisition system for measuring the curing temperature of mass concrete

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Abstract: Timely temperature control in curing newly placed mass concrete is one of the major factors in forming quality concrete. Quick action is necessary to ensure proper designed strength of concrete and avoid cracking when the temperature of the concrete constantly changes. Generally, an automatic recording thermo-hygrograph is used to measure the curing temperature of mass concrete, but the recorded temperature data has to be obtained manually and checked before taking action, such as covering the concrete. While wireless data acquisition is being applied in a growing number of industries, this technology is applied to several fields in the construction industry, such as communication. Therefore, in this study, a wireless data acquisition system is introduced for obtaining the curing temperature of the newly placed mass concrete. Furthermore, with this system, obtaining real time temperature data and taking quick actions for controlling the temperature of mass concrete is possible.

Keywords: Wireless Data Acquisition System, Concrete Temperature, Curing Management, Mass Concrete.

1. INTRODUCTION

The quality of concrete is largely governed by the curing temperature during the first few weeks. Especially in the case of mass concrete, the curing temperature during the first few weeks affects not only long-term strength but also early age strength [1]. Obtaining sufficient early age strength is important for early form stripping and progressing coming work. Generally, the curing temperature needs to be controlled to avoid volume change differentials and restraint result in tensile strains and stresses that may cause cracking [2].

Therefore, to assure quality steady measuring of the curing temperature is undertaken in most construction sites to avoid cracking in mass concrete structures. Nevertheless, other cracking prevention measures are often required to avoid cracking resulting from thermal stresses that occurs from heat arising from hydration, but these measures' performance are insufficient. These precautionary measures use hydration heat and thermal stress analysis to (1) create the optimal mass concrete mixture, (2) ensure the optimal curing method, or (3) determine where to bury thermometer sensors inside the concrete to measure and control the curing temperature.

In some cases, they measure and control the curing temperature, focusing solely on the temperature of the concrete itself, not the ambient air temperature. However, in most cases, the ambient air temperature can greatly differ from the temperature inside the concrete. Furthermore, the curing temperature of mass concrete structure changes frequently. Therefore, steady observation is required. An automatic recording thermo-hygrograph is generally used in measuring the curing temperature of mass concrete, but the recorded temperature data had to be obtained and checked manually before taking proper actions. In other words, a systematic and steady measuring of curing temperature is insufficient. In order to maintain oversight and to prepare for subsequent phases, practical and realtime methods of measuring and controlling of curing temperature is required.

This paper proposes a wireless data acquisition system for obtaining the curing temperature of newly placed mass concrete in realtime. Through this system, one can obtain and monitor temperature data in the office, through a computer. This system is remarkably useful in concreting during cold weather when temperature differences increase rapidly,

thereby allowing for quick action to ensure quality of the concrete.

2. MASS CONCRETE

Mass concrete is narrowly defined to be a concrete structure consisting of section of at least 80cm in length. After concreting this structure, temperature differences between the highest internal temperature of mass concrete structure and the air temperature are expected to be greater than 25ºC through hydration heat [3]. More broadly, the technological aspects of mass concrete are also relevant to any concrete member of such dimensions that the thermal behavior may lead to cracking unless appropriate measures are taken [1]. To avoid such cracking, there are many measures that could be taken, such as using proper materials, e.g. using cement with low hydration heat, and curing. However, when the weather cools suddenly, the only method for avoiding cracks in mass concrete is curing in a proper manner. For example, when the interior temperature of mass concrete increases, the surface temperature of the mass concrete needs to be kept warm enough to avoid sudden temperature differences between the interior and exterior of the mass concrete structure. Therefore, this paper presents proper curing method through wireless data acquisition system for observing curing temperature changes.

2.1 Thermal property of mass concrete

The thermal property of mass concrete significantly influences the volume change of mass concrete. The generally large size of the mass concrete structure has the potential for significant temperature differentials between the interior and the exterior surface of the structure. The accompanying volume change differentials and restraint result in tensile strains and stresses that may cause cracking are detrimental to the structural design [2].
As concrete has low thermal conductivity, the heat generated inside the massive concrete structure escapes very slowly unless aided artificially. Thick mass concrete structures will take several days or weeks to reach a thermally stable condition. A 1.5m (5ft) thick wall requires a week to reach thermal stability [2]. So, during thermally unstable phase placed mass concrete requires a continuous and appropriate curing.

2.2 Arisen problem in curing mass concrete

Especially in cold weather, when sudden temperature decrease takes place, mass concrete temperature variation increases, leading to cracking. To avoid this phenomenon continuous observation is required. The worker needs to know when the temperature differences occur and must react immediately. Currently, automatic recording thermo-hygrographs record the temperature history but continuous observation is not convenient. As automatic recording thermo-hygrographs are installed next to the structure, the worker needs to go to the structure to check the automatic recording thermo-hygrograph. However the inconvenience of this approach results in sparse or occasional observation. Therefore, in some cases, the proper action is either taken too late or neglected. To solve this problem, observation needs to be convenient and the temperature history needs to be observed in real time.

3. WIRELESS COMMUNICATION SYSTEM

Wireless communication technology has made great strides in many fields, enhancing their function and management and saving human effort and time. One example is the walkie-talkie, which has improved not only voice communication in the field but also the method of interchanging of data and information by saving time. Wireless internet links carry data traffic from any remote jobsite to more centralized or convenient off-site locations [4]. This remarkable progress in wireless communication technology made the provision of new wireless information services possible within jobsites to improve their outcome.

3.1 System architecture

A wireless communication system can be constructed in many ways, including circuit-switched cellular modems, specialized mobile radio using packet-switched wireless data systems, packet-switched cellular modems, wireless local area networks, paging systems, satellite-based data communications, and restriction of wireless technology based on data rate requirements. Each of these has specific advantages and disadvantages. Systems with cellular modems are usable wherever data transmission by cellular phone can be conducted. However, cellular modems require a service charge [4]. As a result, when constructing wireless communication system, the property and environment of the jobsites and project need to be considered.

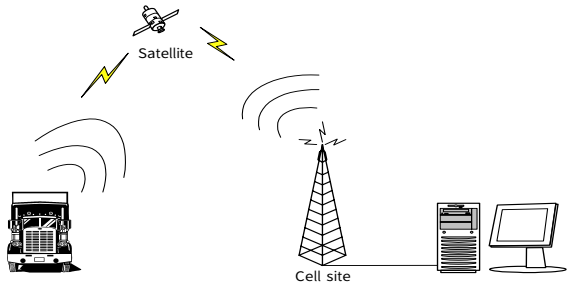

Figure 1. Wireless communication system

(Global positioning system)

3.2 Applied area

Wireless communication systems are used on many jobsites for different areas. Figure 1 shows the architecture of a Global Positioning System (GPS). The GPS is used to keep tracking of construction equipment deliveries in the office [5]. Another example of that wireless communication system is the construction of a sulfur recovery unit (SRU). The foreman of each of crews has access to the wireless communication system to inform the manager of the following information: (1) requests for information (RFI's), (2) materials management, (3) jobsite record keeping and quality control/quality assurance [4]. Each of areas has its own system's architecture which fits best to particular jobsite. The fitness of each system depends on its wireless communication unit. For example, the piezoresistive accelerometer is integrated with the wireless sensing unit for structural monitoring. This system applies the wireless sensing unit with a microelectromechanical system to transfer the data in real time for monitoring [6]. It uses the strength of wireless communication systems for a sensing unit. It can transfer data in real time and it has no service fee. Measurement requires frequent and continuous observation. Often, only recording the history is necessary but in many cases the current measured data must acted upon immediately. For this reason the wireless communication improved piezoresistive accelerometer measurement. Mass concrete curing temperature control is also a measurement exercise that requires a real time data transfer system. This paper proposes an applicable wireless communication system for mass concrete construction.

4. WIRELESS DATA ACQUISITION SYSTEM

Wireless data acquisition system is an enhanced curing management system, ensuring greater jobsite more comfort and quality. The system consists of thermal sensors, data-logger, sending and receiving RF (Radio Frequency) modems and a personal computer to show and check the received data. The RF modem system does not require any service fee and can be used without any legal restrictions. Being as small and light as possible, it is easy to set up and remove.

4.1 Thermometer sensors

Ordinary thermal sensors are listed in table 1. The T-type thermocouple, that has no major complications when applied in many fields, is the most commonly used type of thermal sensor in the fields. However, it comes at a high price.
Considering those properties, a thermal sensitive resister was selected for the wireless data acquisition system. The thermal sensitive resister is physically similar to the T-type thermocouple and is relatively inexpensive. Its measurable temperature range was -30~100°C (error range ± 1°C) and the resistance was 15kΩ. Considering mass concrete's heat of hydration and outside air temperature in cold weather, the thermal sensitive resister was the best choice for measuring the curing temperature.

4.2 Data-loggers and wireless RF modems

One data-logger can receive data through 8 channels at the same time. This makes the curing temperature measurement from different points possible. Also, the measurement period was set to every 1 minute to receive temperature data frequently. Every minute, the RF (Radio Frequency) modem must receive and send data in both directions so that it can first check whether data are received or sent rather than display the data on the monitor. The thermometer sensor connector, which connects to the data logger, was made to set up at once for convenience.

Table 1. Types and properties of thermometers

Type		Usable temperature range(°C)	Div.	Response time	Record/ Control	Cost
Glass Thermometer		-50 ~ 650	0.1 ~ 2	Normal	Not available	Low
Bimetal Thermometer		-50 ~ 500	0.5 ~ 5	Slow	available	Low
Liquid filled Thermometer		-30 ~ 600	0.5 ~ 5	Normal	available	Low
Vapour gas filled Thermometer		-20 ~ 350	0.5 ~ 5	Normal	available	Low
Platinum resistance Thermometer		-260 ~ 1000	0.01 ~ 5	Normal	available	High
Thermally Sensitive Resister		-50 ~ 350	0.3 ~ 5	Fast	available	Average
Thermo-couple	R(PR)	-200 ~ 1200	0.5 ~ 5	Fast	available	High
	K(CA)	-200 ~ 800	0.2 ~ 10	Fast	available	Average
	E(CRC)	-200 ~ 800	3 ~ 5	Fast	available	Average
	J(IC)	-200 ~ 800	3 ~ 10	Fast	available	Average
	T(CC)	-200 ~ 350	2 ~ 5	Fast	available	Average

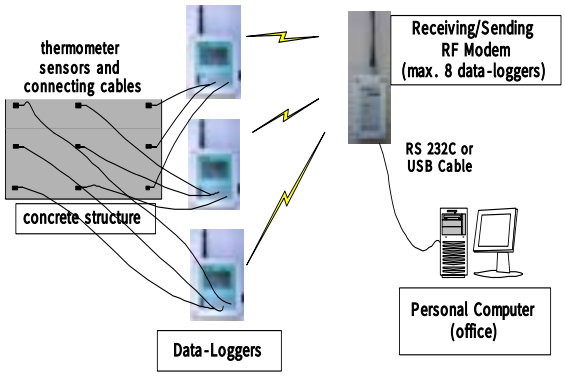

Figure 2. The composition of wireless data acquisition system

4.3 Monitoring

The data, received through the RF modem, are transferred to the personal computer in the office through the RS-232C cable. The data is displayed on the monitor in real time, allowing supervisions to check the thermal condition of the mass concrete and take any necessary immediate action.

5. APPLICATION

5.1 Description of case

The applied mat foundation was the lower part of a foundation that included the elevator pit. The section's depth was about 2.0m~2.5m and the consecutive concreting floor area reached 1200㎡. This huge structure raised concern about cracking due to temperature differences that occurs from hydration heat as time goes by. The daily mean air temperature was between 20ºC ~ 25ºC. Although this air temperature was comparatively high, a high temperature difference between the interior and exterior surface was expected. Therefore a hydration heat analysis program was used to analyze hydration heat and stress. The analysis result showed that the highest temperature in the core of the structure would be 70ºC. Through this analysis, the curing objective was made to keep the temperature difference between interior and outside surface no more than 25ºC. Appropriate mixes of concrete and surface warming planning were provided.

Before concreting the structure, thermometer sensors (thermister) for the wireless data acquisition system were buried to observe the temperature change. Those sensors were buried in the mat foundation's slab at the depth of the upper steel, central and lower steel in three sections. Center, left and right corners.

Figure 3 shows how the data logger and RF modem were installed in the field. The RF modem was installed outside the office window and was connected to the personal computer through an RS-232C cable. The data logger was banded to the exposed steel of the concreted mat foundation's slab structure. The distance between the RF modem and data logger was nearly 300m in a straight line.

Figure 3. Installation of RF modem and data logger

5.2 Results of application

Figures 4 and 5 show the curing temperature history over time. Generally, the wireless data acquisition system measured the concrete slab's temperature well.

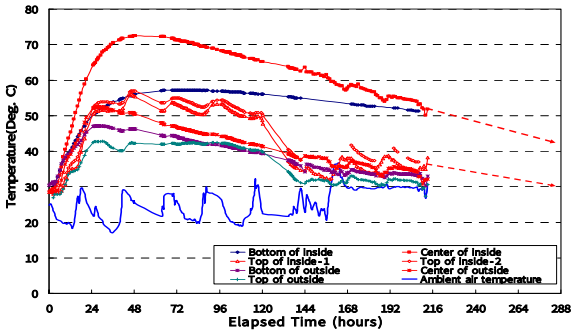

Figure 4. Temperature history output using wireless data acquisition system (1)

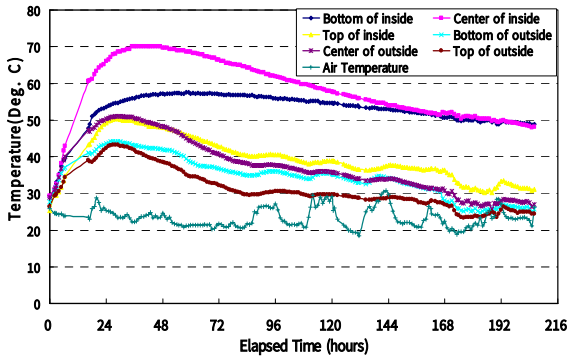

Figure 5. Temperature history output using wireless data acquisition system (2)

As shown in figure 4, by the time of between 120~144 hours, the temperature of the outside surface in the center of the structure had rapidly dropped. This was the case when rain flowed in through the curing mat and waterproof cloth. The structure surface was cooled down by the rain. Fortunately, this situation could be observed in real time through the wireless data acquisition system. Immediate action was taken to stop the cooling. Accordingly, a rapid decrease of temperature was stopped and the proper curing temperature was maintained.

The dotted line in figure 4 shows the expected

temperature history. The expected curing temperature means that the temperature difference between interior and outside surface of the structure will not be greater than 25°C. This estimation resulted in form stripping at 9 days, which was an appropriate time span. The wireless data acquisition system made not only the measurement of the curing temperature ideal, but also the estimation for proper form stripping time possible.

5.3 Validation

The purpose of validation was to verify the promptness and continuity during measuring and saving the changing temperature data. The validation approach was executed with the placed mass concrete in the field. To compare the temperature history, an inspected automatic recording thermo-hygrograph was used. For this test, a thermister-type thermometer sensor was applied to the wireless data acquisition system and a thermocouple to the automatic recording thermo-hygrograph.
The test result is shown in figures 6 and 7. It exhibits the measured temperature history of the mass concrete over time.

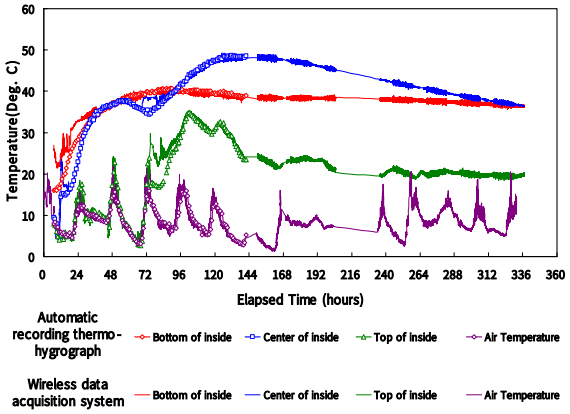

Figure 6. Comparison between automatic recording thermo-hygrograph and wireless data acquisition system (1)

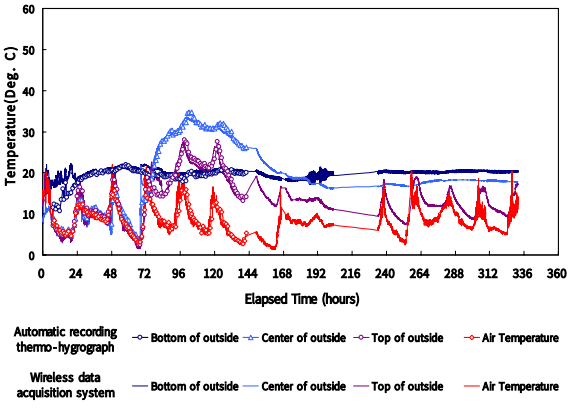

Figure 7. Comparison between automatic recording thermo-hygrograph and wireless data acquisition system (2)

As shown in figures 6 and 7, when both systems' thermometer sensors are buried in the corresponding position, the measured temperature history almost matched each other, regardless of the sensor type or data output method. However, the wireless data acquisition system had a tendency to show occasional discontinuity.
The experiment revealed concerns for the future. During the test, the wireless data acquisition system was powered through the field's power supply; however the power supply in the field is often unstable. Moreover, there are also a possibility that a jamming can occur during the frequent measurement and disturb the transmission between receiving and sending RF modem and data loggers. These need to be observed and corrected in the future.
Through the validation process the promptness and continuity of measuring and saving the steady stream of curing temperature data have been proven. This proven system has been applied in an actual construction site, where mat foundation concreting of a high-rise building was in process, and hereby the applicability to a real situation has been validated.

6. DISCUSSION

Placed mass concrete creates high hydration heat. This high hydration heat results in curing temperature differences between the interior and the exterior surface of the structure and leads finally to cracking. Also a sudden air temperature changes influence the structure's surface temperature. This is one of the critical points in curing mass concrete structures. Currently used automatic recording thermo-hygrograph observations are difficult in real time on a minute basis, rendering immediate action difficult should any problem arise. This makes the curing process useless and inadequate. The purpose of this paper seeks to compensate for this inadequacy by presenting wireless data acquisition system to obtain the curing temperature of newly placed mass concrete in real-time and properly control curing temperature differences in the structure.
The wireless data acquisition system solved this problem by using an RF modem and the data-logger for observing the curing temperature data in real time in the office. This system was validated and applied in an actual construction field successfully. Moreover, the temperature history of this system compared with the automatic recording thermo-hygrograph, did not show a significant difference. The advantage when using the wireless data acquisition system was that any temperature change could be observed in real time, resulting in immediate effective timely action. This is the critical point of the wireless data acquisition system.
Furthermore, the wireless data acquisition system predicted a proper form stripping time. The form stripping time is the most influencing point in shortening the construction duration. The sensors,

buried in 9 points of the structure, measure the curing temperature and transfer the data to a personal computer and display the temperature change on the monitor in graph form. The displayed graph makes the estimation of form stripping time possible, which is difficult with an automatic recording thermo-hygrograph, as it does not measure the curing temperature or display the output in that manner.
The wireless data acquisition system's multi-point measuring sensors make curing control and analysis possible. Moreover, the wireless communication's application enables convenient observation of the curing temperature history, providing a better working environment. Finally, this system improves the quality management of mass concrete structures.

7. CONCLUSION

In this paper a wireless data acquisition system was successfully applied in practice. Currently, a mass concrete structure's curing temperature measurement is executed by automatic recording thermo-hygrographs. However, this tool exhibited problems in real time observation. To overcome this limitation, an improved measuring method is presented to avoid cracking in the mass concrete structure. The wireless data acquisition system's critical feature is its real time data transmission. As the curing temperature may change at any time for any reason, the wireless data acquisition system improved the curing method by applying a wireless communication system. Furthermore, this system shows the possibility of application in managing the quality of a mass concrete structure. Further research is recommended to cure and manage the quality of the mass concrete.

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INFORMATION SHARING SYSTEM FOR PROCESS MANAGEMENT

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ABSTRACT: In one construction production process, a huge quantity of data is used and it has complicated relation among companies and systems. But the system environment which associates it is not established by the present construction production. Therefore, when the event which blocks a process plan occurs, great cost occurs in change of a process plan. This paper shows how to realize the increase in efficiency of management by the information sharing system using XML technology and SVG technology. And, the "Parts and Packets unified architecture" system using RFID and Active Data Base shows the technique of preventing the increase in the cost accompanying change of a process plan.

KEYWORDS: Glue Logic, Parts and Packets, Active Data Base, RFID, XML, SVG

1. INTRODUCTION

It is almost the case for two or more companies to cooperate and to advance a process in the present construction production. And the amount of data used by one construction production process reached the huge number, and is entangled intricately among companies or in the company. However, although it is clear that these data has causal relationship, the system environment which connects it is not established by the present construction production.

And, in construction production, a detailed process plan is decided in advance, and, usually two or more companies concerned with the construction production and a section do work on the basis of a process plan. But, since various events which interfere with a process plan actually occur, the process plan decided first is changed in many cases. Since the event which blocks a process plan leads to the increase in direct cost, it needs to change a process plan so that damage may be suppressed to the minimum. But, since the amount of data used by the construction production process has huge and complicated relation, it is the present condition to have required the difficulties for change of a process plan.

2. THE OUTLINE OF A SYSTEM

By introducing a parts and packets unified architecture system and an information sharing system aims at reduction of the increase in efficiency of the management about redundant data, and the formation of cost increase accompanying change of a process plan to the problem of construction production.

The structure of "Parts and Packets unified architecture" is made into the precondition at introduction of a system. This embedded the minute radio tip called RFID to the Construction Department article, and has pointed out beam structure with a string for ID information to each Construction Department article. It is possible to read each ID information with un-contacting type reading equipment in this article. This reading equipment is installed in the important reference point of a construction production process, and the passage status is collected. Incidentally, in this research, the important reference point in this construction production process is called the "gate".

And, there is an Active Data Base (the following, It is referred to as ADB.) as an important base of a parts and packets unified architecture system. ADB carries out the optimal rescheduling, when the event which blocks a process plan occurs. And it has a function for reissuing directions required for the persons concerned. That is, ADB is an event drive type schedule optimization system using

the incoming signal from a gate.

In addition, ADB is based on the Glue Logic currently developed at the Tokyo Electric communication university and the Takata laboratory. The Glue Logic is a base system for control which makes it possible to perform processing autonomously to a specific input.

About the information sharing system, the Web application system using the database of XML form was adopted. Since XML has the feature which can absorb the difference in a data structure flexibly, it can absorb the difference in the data format over the company engaged in construction production, and the system.

And, the ubiquitous environment which can receive required information, without asking places, such as an office, a factory, and a construction site, is also offered by enabling perusal of the data of the construction production integrated by XML by the Internet. About the display screen, it is considering as the operation design which can pull out information by performing interactive operation on the drawing focusing on the drawing information for maintaining common recognition among construction productional-relations persons. Operation which relates required information with a drawing image and can pull it out intuitively by this is realized.

3. DETAILS OF A PROTOTYPE SYSTEM

The following items were made into the requirements for a system in building the prototype of an information sharing system.

(1) The database used by the system is made into XML form.
(2) System form is made into a Web application system.
(3) It is made the structure where a system is connectable with ADB.
(4) The reference function to a database is mounted.
(5) It is made the interface in which intuitive operationis possible.
(6) The data format of drawing information is made into SVG form.

About (1), Use of XML is the optimal in order to unify the construction production data over the company and the system.

About (2), it is possible in the Internet to acquire information, without asking a place. Therefore, a system is made into a Web application system and it considers as the structure which can disclose information to the Internet.

About (3), By cooperating ADB and the information sharing system for optimizing a schedule, the increase in efficiency to a construction production process is raised in multiplication.

About (4), the construction production data accumulated by continuing employing a system serves as a huge quantity. Therefore, a reference function becomes indispensable.

About (5), the user of a system is not necessarily the expert of a computer. Therefore, an interface which can get information by carrying out interactive operation to the drawing information to display and which use tends to make intuitive shall be built.

About (6), in order to make a CAD drawing peruse by the Internet and to give interactive operation, SVG form is the the best for the data format of drawing information.

In this research, the prototype of an information sharing system was created on the assumption that these requirements for a system. An information sharing system is accessed via the Internet and the screen with which arbitrary things were searched is shown in Figure 1. And the screen which displayed the detailed information on the searched thing is shown in Figure 2.

An information sharing system can be accessed by the browser through the Internet. And it is possible to search arbitrary things from a vast quantity of construction production data accumulated in XML form. The link to thing information is stretched to the reference result, and the information can be perused easily. It is possible for information to be related with the object of a drawing, to click an object, and to acquire detailed information interactively. And the structure which each object is made to display the newest process situation according to a color, grasps a process situation visually, and can start action because ADB cooperates is realized.

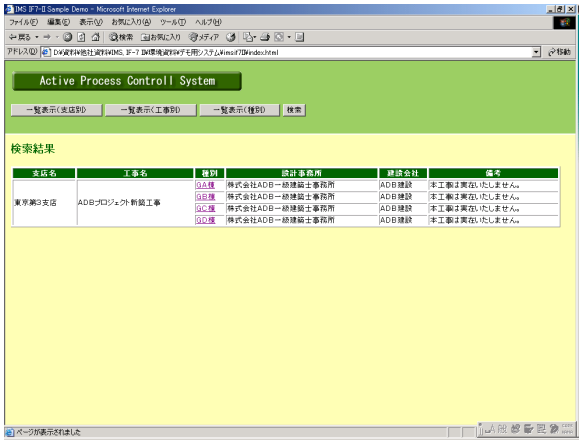

Figure 1 The display screen of a reference result

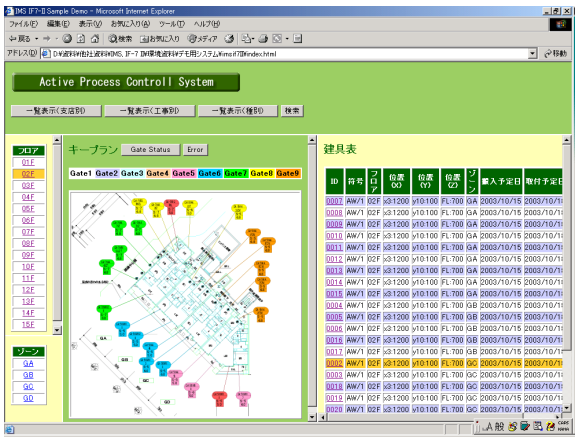

Figure 2 The detailed information screen of a reference thing

4. CONCLUSION

By research of this fiscal year, the prototype of an information sharing system was operated, construction production data was unified in the database of XML form, and a possibility that information would be sharable among companies was shown. And by making it cooperate with ADB also showed a possibility that it might become the high interface of convenience over the rescheduling of a construction production process.

In the prototype system built this time, XML is made to collect construction production data and this structure is set as the center of a system. It is thought that it can respond flexibly when considering range extension of the systematization in construction production, since the system based on such XML is very excellent in extendibility.

The function to manage the layer structure of security strengthening of a system, and a drawing and attribute information is due to be added from now on. Furthermore, formal employment shall be put into a view and the load test and durable test to mass data of construction production shall also be considered.

STUDY OF ZMP MEASUREMENT FOR BIPEDROBOT USING FSR SENSOR

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Abstract: This paper discuss a method measuring ZMP for biped robot. We obtained feet-bottom pressure distribution using FSR sensors attaching feet-bottom. We calculate value of ZMP coordinates that is the center of gravity for biped robot using their pressure distribution. Value of Biped Robot ZMP coordinates always exists in feet-bottom. When walking limbs of biped robot are controlled, inverse kinematics use method supposed by author. We introduce it in this paper.

Keywords: Biped Robot, FSR Sensor, ZMP, feet-bottom

1 INTRODUCTION

To improve life quality, human request robot that can alternate one's work. This robot is calling humanoid. Robot Technology goal is humanoid. We may try humanoid robot being. Recently, study of humanoid robot is proceeding in many place. Generation of car model robot driven by wheels sooner or later replace with wakling robot generation. And, we might oppose that we may replace human effort as role of home robot as well as industry robot. Walking is a essential basal condition so that anthropomorphic robot adapts to human environment.

In this study, author formerly makes a small-sized humanoid oneself. This humanoid names DORRAE. Humanoid DORRAE is korean that means pulley. Pulley symbolizes balance and control of force. From a robot kinematical point of view, DORRAE is robot which was made farther nearly human structure. Existing DORRAE gait formula is method realized via sequential pattern tracing using walking pattern reference. But, the center of gravity caused by robot weight, that is, Zero Moment Point(ZMP) must be measured and controlled in realtime operation so that robot can overcome to tumble due to unexpected noise. therefore, measuring ZMP is preceded.

In this paper, when we control humanoid robot walking, the upper limbs is fixed and the nether limbs is controlled using inverse-kinematics method proposed by author. In this condition, for measuring and maintaining ZMP, we use to attach four FSR sensors a foot in exiting study but three FSR sensors a foot in this paper. This paper experiment shows measurement ability to attach three FSR sensors per foot.

2. ABOUT DORRAE ROBOT

DORRAE appearance is showed by figure 1.
Special feature of DORRAE is 1) autonomous locomotion 2) remote robot control(using Bluetooth) 3) realization of varying posture made by twenty joint.

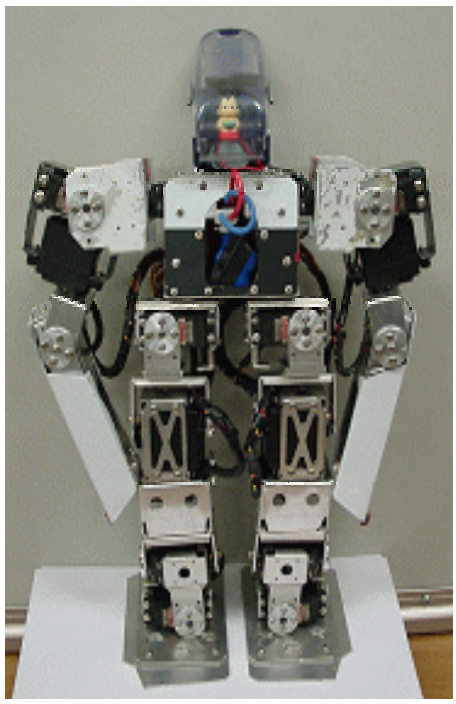


Figure 1. Biped robot made for experiment

DORRAE has twenty degree of freedom(DOF) which consist of each two unit that arm has four DOF and leg has six DOF. Height is 350mm and weight is 2.5kg. DORRAE joint organization is like figure 2.

Main processor of DORRAE is ATmega128 which is RISC 8bit prosessor AVR. Therefore, we can remote control using Bluetooth.
If robot tumbled, Robot can pick oneself up as it trace sequential pattern reference.
In the future, when robot is tumbled, it will add function picking oneself up via balance and gyro sensor.

Joint			quantity
head		roll	0
		pitch	0
		yaw	0
arm	shoulder	roll	2
		pitch	2
		yaw	2
	elbow	roll	0
		pitch	2
	wrist	roll	0
		pitch	0
	hand	pitch	0
waist		roll	0
		pitch	0
		yaw	0
leg	hip	roll	2
		pitch	2
		yaw	2
	knee	pitch	2
	ankle	roll	2
		pitch	2

figure 2. DORRAE joint formation

3. JOINT CONTROL

DORRAE is modeling like figure 2.

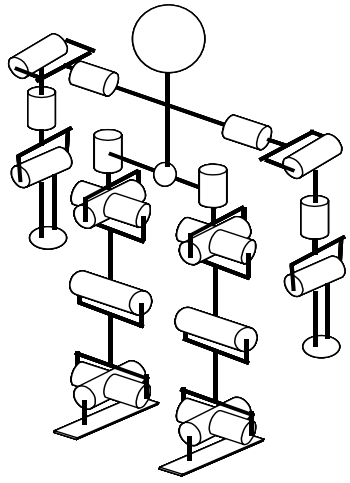


Figure 2. Biped robot(DORRAE) model

In order to control robot, kinematics modeling must be preceded. Generally, biped robot is been modeling as kinematical analysis divisor like Denavit-Hartenberg notation(D-H notation) applying to manipulator(robot arm) which often use the progress of industrial work. But it is difficult to realize low-cost microprocessor because this exiting methods have long operation time. By the way, Walking human leg is working space and motion is more limitary than manipulator. Thus, modeling method which can reduce operation time was issued by author. [4]
Simply to discuss this, Walking demanded motion of leg regard as three motion. The three motion is to regulate leg length using knee, to move foot to front or back and to move foot to left or right. Thus, we obtain angle of each joint through degree of the three motion.

3.1 Re-modeling about leg length
Prismatic joint structure regard as knee joint of robot like figure 3, and then it analyzes.

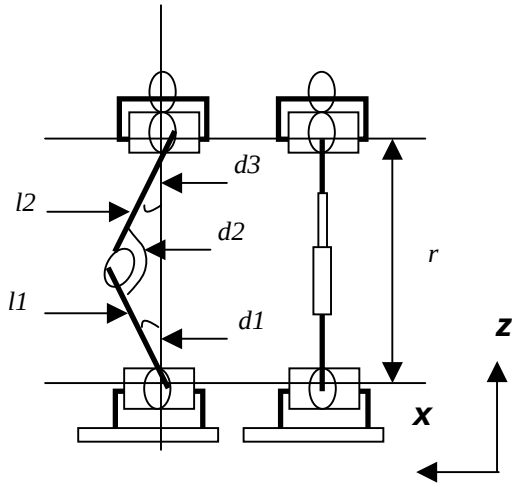


Figure 3. Re-modeling to regulate leg length using knee

3.2 Re-modeling to move foot to front or back

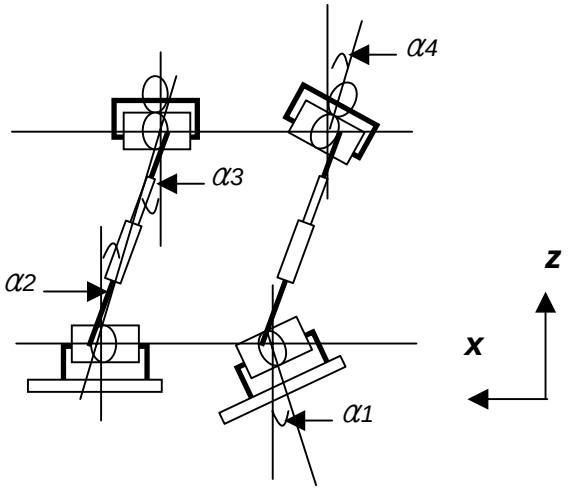


Figure 4. Re-modeling to move foot to front or back

Like as figure 4, four variables which is α1, α2, α3, α4 assign in two joint took part in motion to move foot to front or back. α2, α3 move to same angle and α1, α4 indicate direction angle of the upper and lower each joint. By α2(=α3), The value of x coordinates from center to foot is obtained.

3.3 Re-modeling to move foot to left or right

Like as figure 5, four variables which is δ1, δ2, δ3, δ4 assign in two joint took part in motion to move foot to front or back. δ2, δ3 move to same angle and α1, α4 indicate direction angle of the upper and lower each joint. By δ2(=δ3), The value of y coordinates from center to foot is obtained.

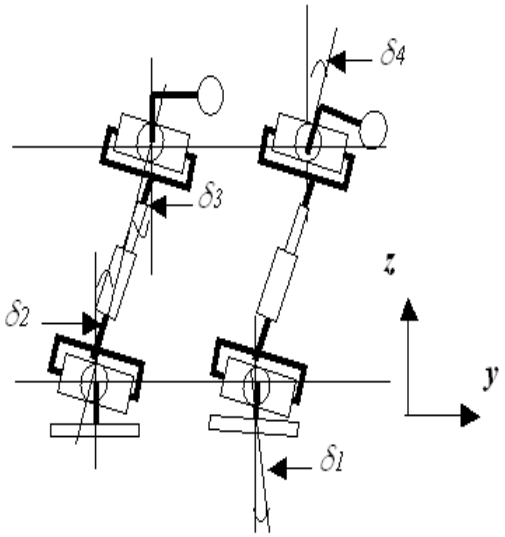


Figure 5. Re-modeling to move foot to left or right

4. ZMP MEASUREMENT

We obtained feet-bottom pressure distribution using FSR sensors attaching feet-bottom. We calculate value of ZMP(Zero Moment Point) coordinates that is the center of gravity for biped robot using their pressure distribution.

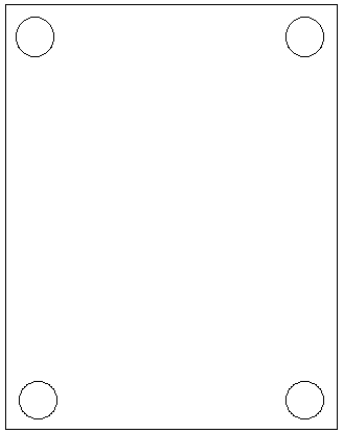
Formerly ZMP Measurement is used to attach feet-bottom to four FSR sensors like Figure 3. In this paper, it is used for ZMP Measurement to attach feet-bottom to three FSR sensors like Figure 4. We made a experiment foot like Figure 9.(b) and equation to calculate pressure about each coordinates. We lay a counterweight in each coordinates and then measured all FSR value. We contrasted pressure value based on equation with measuring pressure value. Using experiment result we made equation to calculate ZMP coordinates value about each FSR sensor value. This experiment show that equation to calculate ZMP coordinates value proposed by author is adequate.

4.1 The existing method of ZMP measurement

In order to obtain precise ZMP, we install accelerometer in the center of all link gravity and then calculation ZMP using value measured these. But, this method is difficult to realize system. more simplicity and efficient method is to measure ZMP using FSR(Force Sensing Resistors). Method measuring ZMP using FSR seek the center of gravity. Using FSR, we easily trace movement of ZMP. Like as equation (1), we can obtain the coordinate values of ZMP.

$$x_{ZMP} = \frac{\sum_{i=1}^{4} f_i x_i}{\sum_{i=1}^{4} f_i}$$
$$y_{ZMP} = \frac{\sum_{i=1}^{4} f_i y_i}{\sum_{i=1}^{4} f_i} \quad (1)$$

When we calculate the coordinate values of ZMP, absolute magnitude of force measured via FSR isn't significant. It is because relative value is decided.



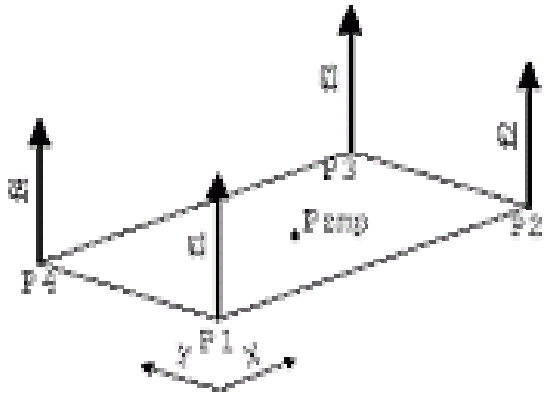


Figure 6. Attached four FSR sensors a foot

In figure 6, *a, b, c, d* are measured values via p1, p2, p3, p4. When *na, nb, nc, nd* (*n is optional integer*), we anticipate to calculate same ZMP constantly. Hence this has two meaning.

First, If force values measured via each FSR is very

small, ZMP seriously is changed by measured error. Second, with make foot-bottom precisely it must have structure that force distribution uniform. If it isn't so, measured ZMP values are imprecise.

4.2 The improved method of ZMP measurement

When measured FSR values are f1 >fmin, f2 >fmin, f3 >fmin, f4 >fmin, value of optional one - for instance, f1 - can alternatives value used by equation (2). Thus, to use three FSR that isn't four FSR can reduce the number of FSR. It is proved by experiments executed in this paper.

$$f1 = f2 \times f4 / f3 \quad (2)$$

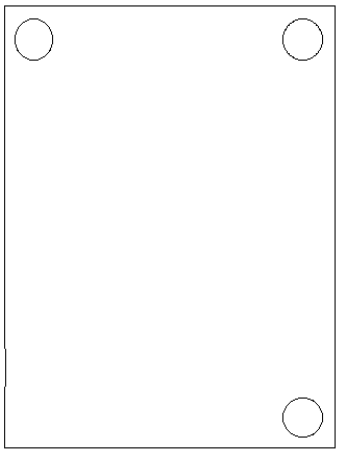


Figure 7. Attached Three FSR sensors a foot

4.3 Design of biped robot foot-bottom for ZMP measuring

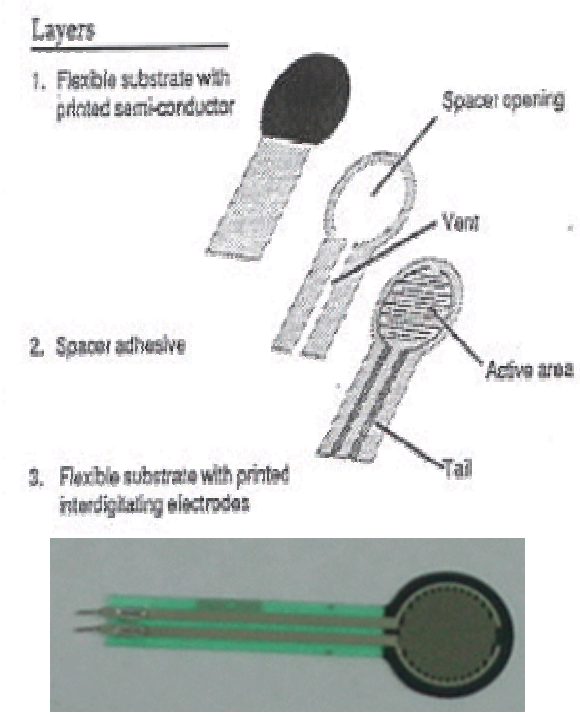
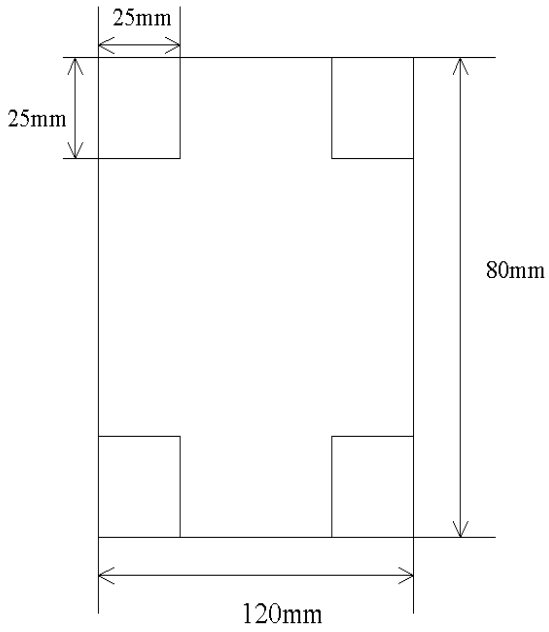


Figure 8. FSR sensors attaching in biped robot foot-bottom

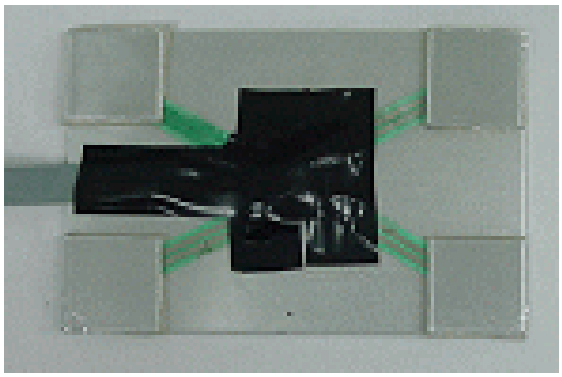
Shown figure 8, force Sensing Resistors(FSR) are a polymer thick film (PTF) device which exhibits a decrease in resistance with an increase in the force applied to the active surface. Its force sensitivity is optimized for use in human touch control of electronic devices. FSRs are not a load cell or strain gauge, though they have similar properties. FSRs are not suitable for precision measurements.

When we calculate the coordinate values of ZMP, absolute magnitude of force measured via FSR isn't significant. It is because relative value is decided.

Like as figure 9.(a), length(axis of x) is 120mm, width(axis of y) is 80mm, and four corner which support upper body of foot-bottom are a regular square that length of a side is 25mm. Both surface attaching FSR select material to be able to press on it softly then to absorb shock. figure 9.(b) is the picture of feet-bottom made by author.



(a) Standard of foot-bottom



(b) Picture of foot-bottom

Figure 9. Foot-bottom attached Four FSR Sensors

4.4 ZMP measuring experiment

The value of coordinates for experiment is that axis of x is value from +40mm to -40mm maintaining 10mm gap and axis of y is value from +20mm to -20mm maintaining 5mm gap. This is the appointed value of coordinates(o).

When it is inflicted that weight of 3kg on surface that the appointed value of coordinates is the center of circle and a diameter is 10mm, pressure value of f1,f2,f3,f4 is measured. To assign f1,f2,f3,f4 to equation (1), the measured value of coordinates(+) can be obtained. To subtract the appointed value of coordinates(o) from the measured value of coordinates(+), an error be obtained. Figure 10 shows the appointed value of coordinates(o) and the measured value of coordinates(+).

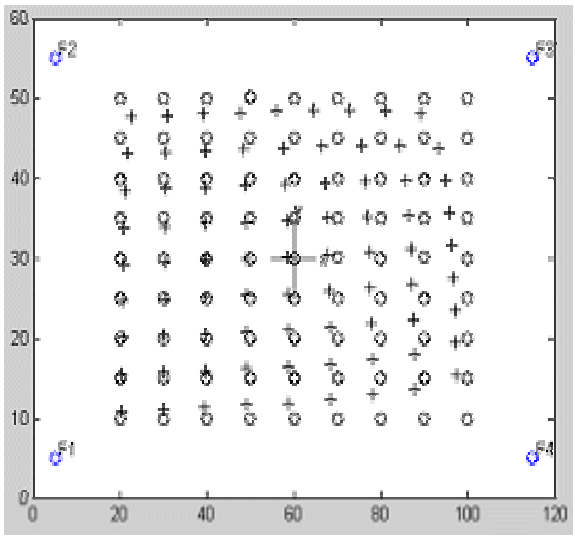


Figure 10. The measured value of coordinates(+) using four FSRs about he appointed value of coordinates(o)

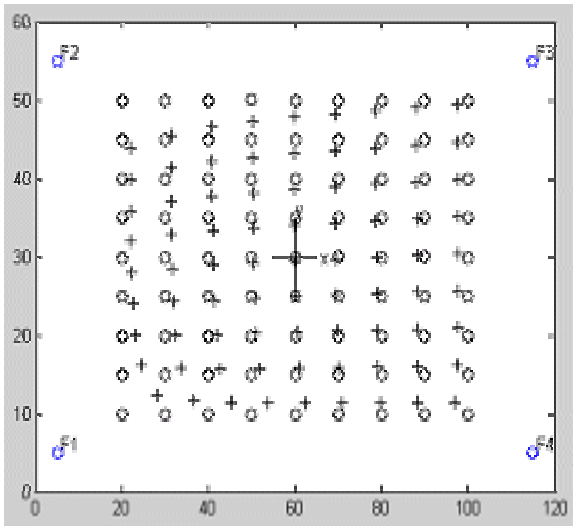


Figure 11. The appointed value of coordinates(o) and the measured value of coordinates(+) using three FSRs that F1 be replaced by equation (2).

In this way, the measured value of coordinates(+) is obtained to replace one by one input value of FSR as equation (2). although we remove one among F1, F2, F3, F4, the result doesn't very differ from using four sensor and other three sensor. Figure 11 shows the appointed value of coordinates(o) and the measured value of coordinates(+) using three FSR that F1 be replaced by equation (2).

4.5 The result of experiment

To subtract the appointed value of coordinates(o) from the measured value of coordinates(+) in section 4.4, an error be obtained. figure 12 shows average errors.

used FSRs	average error(mm)	
	coordinates of x	coordinates of y
F1, F2, F3, F4	-1.97	-0.67
F2, F3, F4	-3.04	-0.79
F1, F3, F4	-1.83	0.01
F1, F2, F4	-2.03	-0.50
F1, F2, F3	-3.71	-0.65

Figure 12. Average errors with used FSRs

As a result of this experiment, when we measure the center of robot gravity, although we use optional three FSRs among four FSRs, these errors don't cause problem which make tumble robot. Thus, this experiment shows that to measure ZMP using this method isn't influence.

5. CONCLUSION

Processors of DORRAE are ATmega128 which is RISC 8bit prosessor AVR. Prodessors are the number of two. one is main processor which control motion pattern. another is slave processor which control the 32 of RC-servo simultaneously. unsynchronous serial communication is used between main processor and slave processor.

In the result, to attach three FSRs which is four FSRs in foot-bottom , we can measure ZMP. Thus, for the first time, humanoid can flexibly adjust against the ground condition and the force which is caused to outer disturbance.

Hence, compensation algorithm in static and dynamic status should study.

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Development of Vision System on Humanoid Robot HRP-2

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Abstract: Ministry of Economy, Trade and Industry of Japan had run an R&D project on humanoid robotics since 1998 for five years. In the first two years, platforms for humanoid robotics research were developed. In the next three years, researches were carried on for five different applications. We joined a group of the cooperative works by a human and a humanoid robot and took charge of a robot vision system. We designed a stereo camera module on a humanoid robot, developed some calibration methods and incorporated 3D image processing algorithm into the robot. Through this R&D, we showed a possibility to apply a humanoid robot for field of construction.

Keywords: humanoid robot, HRP-2, stereo vision, 3D image processing, VVV

1. INTRODUCTION

December 1996, Honda presented a humanoid robot ,"P2". This incident accelerated the research and development of humanoid robotics in Japan. Ministry of Economy, Trade and Industry of Japan had run an R&D project on humanoid robotics [1] since 1998 for five years. In the first years, platforms for humanoid robotics research were developed. In the next three years, researches were carried on for five different applications. The applications were maintenance tasks of industrial plants, building and home management services, human care services, operating industrial vehicles and cooperative works by a human and humanoid robot. We joined a group of the cooperative works by a human and a humanoid robot [2]. and took charge of a robot vision system.

We designed a stereo camera module on a humanoid robot, developed some calibration methods and incorporated 3D image processing algorithm into the robot.

2. TECHNICAL GOAL

The goal of the cooperative works by a human and humanoid robot was to build a terrapin hut together. Fig. 1 illustrates an image of the works. Two typical tasks were selected. One was to carry an external wall panel, and another was to mount the panel on the frame of a house. Some technologies were needed for achieving the following tasks.

1) Hardware/software to walk on uneven surfaces,

and to prevent damage in the event of tipping
2) Environment recognition technology for working on a construction site
3) Communication between human and robot
4) Software to control arms and legs cooperatively

We took charge of “the environment recognition technology”. Developing the robot eyes for recognizing an environment and applying for detecting unevenness of a ground, searching a panel on the construction site and measuring the panel position and the grasping point on the panel.

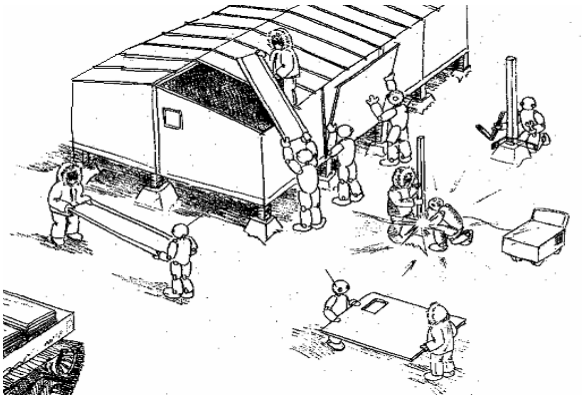
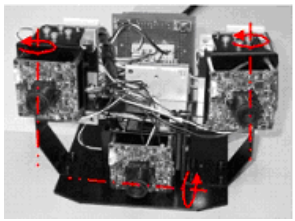


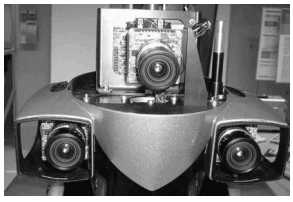
Fig. 1. Cooperative Works

Fig. 2. HRP-2



a) Prototype System

b) System for HRP-2P



c) System for HRP-2

Fig. 3. Robot Vision

3. HRP-2

In order to achieve four technologies described above, a new humanoid robot, the name was HRP-2, had been developed. Fig. 2 shows the HRP-2. HRP-2's height is 1539mm and the weight is 58 kg including batteries. It has 30 *deg* of freedom (DOF) including two DOF for its hip. The cantilevered crotch joint allows the robot to walk in a confined area. Its highly compact electrical system packaging allows it to forgo the commonly used "backpack" used on other humanoid robots and to get up after falling. It has 6DOF force-torque sensors on each wrist. When HRP-2 carries a panel with a human operator, it senses force and torque in order to decide the walking direction and velocity.

4. VISION SYSTEM

HRP-2 has a trinocular stereo camera system on its head. The vision system was designed under restrictions which include the limit of weight, the limited space of the head and the measurement accuracy for the program. Versatile Volumetric Vision: VVV system [3], which had been developed by the 3D vision group of the AIST, was implemented for the HRP-2 image processing software.

4.1 Hardware

On the stages of developing the hardware, we made three types of system step-by-step. Fig. 3 shows the prototype, the system for HRP-2P and the system for HRP-2. The HRP-2P is a prototype model of the HRP-2.

1) Prototype Vision System

Resolution of each camera is 480x640 pixels and the intensity resolution is 256 grey level. Two horizontal cameras are separated by 120mm, and the third camera is located 60mm below the two horizontal cameras. Three cameras are used in order to increase 3D measurement accuracy and reduce stereo correspondence errors. A Stepping motors behind each camera changes the convergence according to the distance from the cameras to an object. In order to examine performances of the prototype system, it was mounted on HRP-1, which is based on Honda humanoid robot P-2, and captured several scenes. Fig. 4 shows the prototype vision system mounted on HRP-1. The experiments revealed that the cameras rotation mechanisms were vibrated due to a vibration generated from the motors of the robot joints

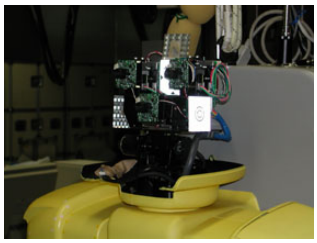


Fig. 4. Prototype Vision System on HRP-1

2) System for HRP-2P/HRP-2

For requirement of the limited weight, we could not use the motors that generate enough torque to stop the vibration of the camera's rotation mechanisms. Therefore a wide-angle C-mount lenses having a single focal length (8mm) was used to capture distant and nearby scenes simultaneously. The camera's shutter speeds were variable and adjusted automatically under several lighting situations. The total weight is less than 700g.

We confirmed performances of the vision system with the system for HRP-2P and designed the last system for HRP-2. The main differences between the system for HRP-2P and the system for HRP-2 are the length of the cameras base-line (120mm for HRP-2P, 140mm for HRP-2) and the appearance of the shields.

4.2 Software

The software for controlling HRP-2 was developed with Open Architecture Humanoid Robotics Platform (OpenHRP) [4]. The OpenHRP is a software platform for humanoid robotics and has been developed since previous term of the HRP. The OpenHRP consists of several modules to control body, to recognize voice, to generate voices and etc, and a task manager which integrates those modules. With this structure, each module can be developed independently and integrated to the software for controlling robot easily.

Stereo vision module was developed for one of the modules of OpenHRP. Each module of OpenHRP can be executed in a computer on a TCP/IP network. In order to connect the stereo vision camera on the robot's head, the stereo vision module was implemented in a computer inside HRP-2. When body control module sends a command to the stereo vision module, it carries out image processing and sends back a result.

5. DISTORTION CORRECTION

The captured images with HRP-2 were distorted due to the shields in front of the stereo vision system, and the wide-angle lenses. Since these distortions had adverse effects on image processing, we had to develop two distortion correction methods [5].

5.1 Shield Distortion

The cameras were covered by shields as shown in Fig. 5. It was difficult to derive a distortion model from relationship between a shield shape and a camera position deductively. Therefore we used a reference table which converts distorted image to undistorted one (Fig. 6). First, the camera without shield captures a panel, on which several circles were located periodically. Next the camera with a shield captures the same panel. For all circles in the each image, the positions of a center of gravity are calculated. Using a large circle near the image center as a reference, we can build correspondence of each circle's position between the distorted image and the undistorted image. Transformation for all pixels is performed by interpolation based on the correspondence of all circles.

Fig. 7(a) and Fig. 7(b) are captured images with and without a shield, respectively. Fig. 7(c) is a converted image of Fig. 7(a). Fig. 7(d) shows differences between Fig. 7(a) and Fig. 7(b). Fig. 7(e) shows differences between Fig. 7(b) and Fig. 7(c). In Fig. 7(d), influence of the distortion can be observed as white parts left side of circles. In Fig. 7(e) the white parts are decreasing.

Captured image with a shield becomes too dark to execute image processing. We take longer exposure time for the image with a shield. Therefore in Fig. 6 and Fig.7, the image with a shield is brighter than it without a shield. And circle patterns in Fig. 7(d) and 7(e) is the result of the difference of the exposure time between the images with and without shield. It is independent to the distortion for a shield.

Fig. 5. With and Without Shield

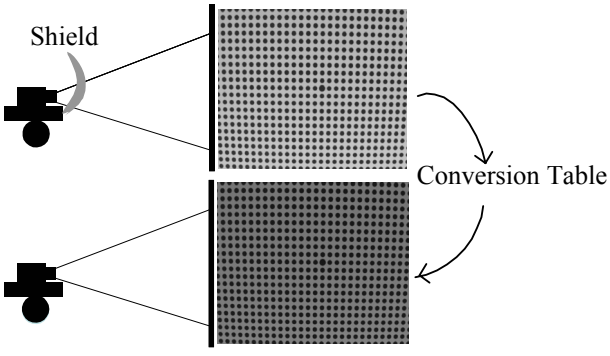


Fig. 6. Distortion for Shield

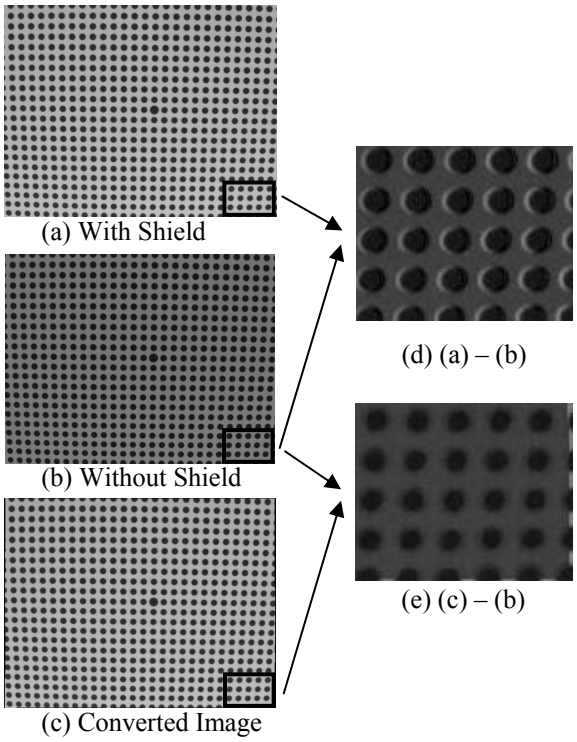


Fig. 7. Correcting Distortion for Shield

5.2 Lens Distortion

Fig. 8 shows aberration, which is caused by wide-angle lens. Relationship between distance from a principal point to a observed point *r'* and distance from the principal point to a ideal point *r* is below.

$$r' = r + k_1 \cdot r^3 + k_2 \cdot r^5 \qquad (1)$$

Parameters, k_1 and k_2, depend on the lens. Usually one coefficient k_1 is sufficient to correct the distortion, however, more coefficients are need for shorter focal length.

In order to correct this distortion, we also use the same image, which is captured for correcting the distortion for the shield. The lattice position **P** on a plane is expressed as follows:

$$\mathbf{P} = i\mathbf{u} + j\mathbf{v} + \mathbf{w} \qquad (2)$$

where *i*, *j* are integers. **u**,**v** are non-parallel vectors and **w** is the origin. The position of the large circle is defined as **w**. Vectors for column and row directions are **u**, **v**. Any point can be expressed by the parameters (*i*, *j*). Data near the image center is generally only slightly distorted for the wide-angle lens, therefore the ideal positions without distortion for all lattice points are calculated using these data. Assigning the ideal positions and the observed positions into Eq. (1) and applying least-square method, we calculate the k_1 and k_2. Fig. 9(a) shows a base image with lens distortion and Fig. 9(b) shows a corrected image using the lens model. Distortion at rim of the image is corrected and the error was less than 0.2pixels.

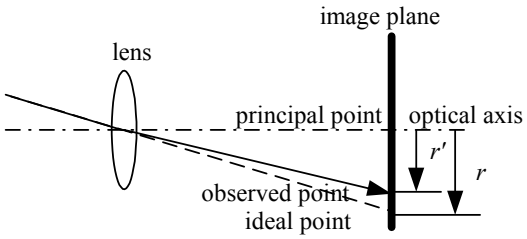


Fig. 8. Distortion for Lens

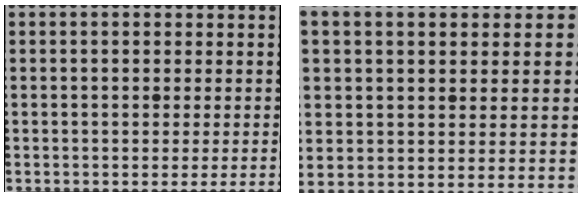


Fig. 9. Correction Distortion for Lens

6. DEMONSTRATION

Carrying a panel cooperatively with a human operator and putting the panel to build a wall of a terrapin hut were the tasks, in which developed technologies of our group were demonstrated. The vision system was used for autonomous tasks in former part of the demonstration.

6.1 Measuring Ground Displacement

HRP-2 could not take its step on 2cm unevenness of the ground. In order to avoid a rough ground, HRP-2 has to detect the range data of the ground [6]. Fig. 10 shows configuration of the robot detecting the rough ground. HRP-2 bends down its head and observes trapezoid area on the ground. In order to obtain the range data of the ground surface, a correlation stereo method is applied to two images captured by right and left cameras. Using a LINUX PC (Pentium3 1.26*GHz* CPU with 256*MB* memory) with acceleration technique proposed by Okada et al. [7], image processing for two VGA size, 256 grey level images could be executed within 4 seconds. Fig. 11 shows the stereo images and the obtained range data.

The ground displacement measurement error due to the discrete value of the disparity is approximately 20*mm*, but with interpolation it can be reduced to approximately 15*mm*. Fig. 12 shows histograms of z (vertical direction) value for a flat floor. Two curves are histograms with and without interpolation, which shows improvement by interpolation clearly. Because the origin of the foot coordinate is fixed on the ankle joint, which is

100*mm* above the floor, it has a peak at –100*mm*.

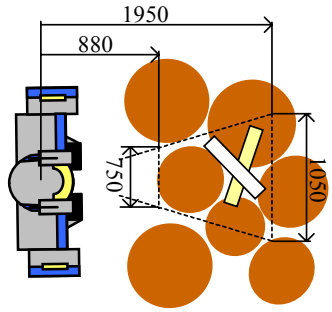
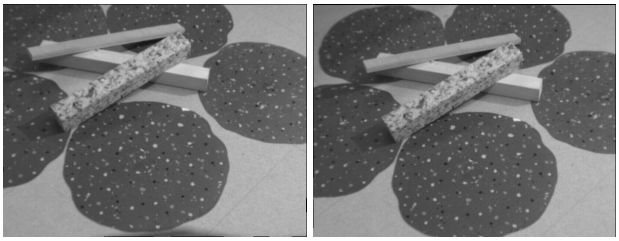
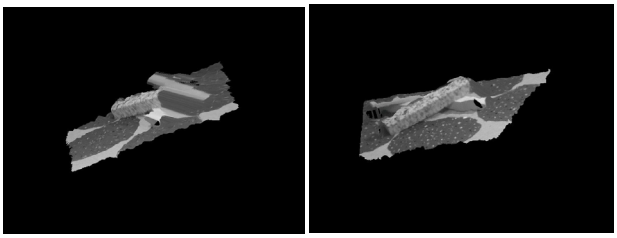


Fig. 10. Watching Uneven Ground



Left Image Right Image



Reconstructed 3D Range Data

Fig. 11. Ground Displacement Measurement

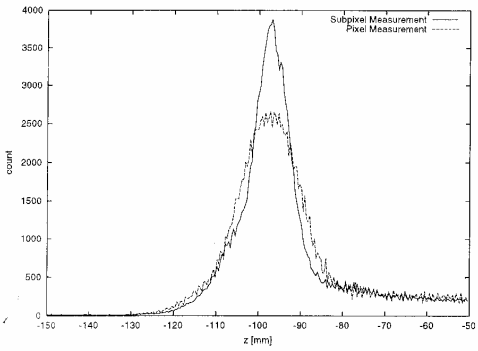


Fig. 12. Measurement Error

6.2 Approaching and Grasping Panel

1) Task Sequences

HRP-2 autonomously searches and approaches a storage site of panels, and grasps a panel end (Fig13). Following is the detailed sequence:

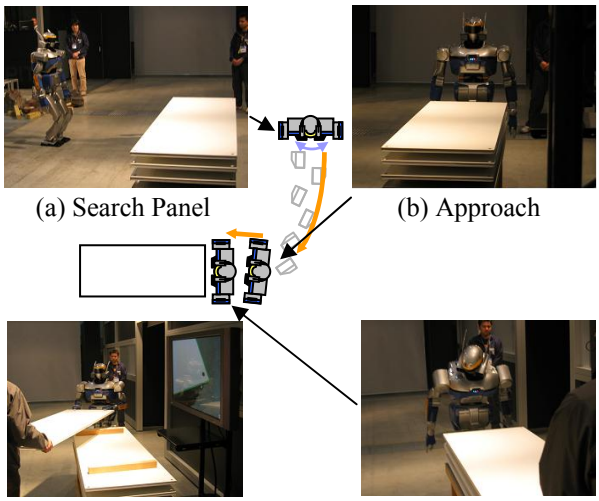
(a) A human operator gives "Start work" voice command to the HRP-2. HRP-2 turns its head to the expected direction of a storage site of panels. The robot captures images and tries to detect the shape of the top of the pile of panels in the scene. When no panel is detected in the scene, it turns the head 10*deg* each and captures images again until the panel is finally detected. When the panel is detected, in order to confirm the result, the robot turns its head straightly to the direction and detects the panel once more. According to the obtained panel position and attitude, HRP-2 calculates the path to the first approaching point, which is 600m far from the end of the panel.

(b) HRP-2 walks the first approaching point. The robot turns its head to the direction of the panel and detects it again. According to the result, the robot walks in front of the panel end.

(c) HRP-2 bends its waist and neck joints and looks up the right near corner of the panel. The robot detects the corner and calculates position and attitude of the grasping point of the panel.

(d) In order to grasp the panel, HRP-2 turns its waist and moves its hands to the adequate position. Then the robot and the operator carry the panel together.

In this sequence HRP-2 compensates a walk error and a vision measurement error. HRP-2 can stably approach the storage of panels and grasp the panel.



(a) Search Panel (b) Approach

(d) Carry Panel (c) Look Corner

Fig. 13. Task Sequences

2) Detecting the Panel and its Corner

A segment-based stereo method [8] in the VVV system is applied to recognize a panel and a corner of the panel. The procedure of the panel recognition at the starting point of the work is as following:

(a) Capturing stereo images simultaneously
(b) Extracting boundary line from the images
(c) Reconstructing 3D structure using segment-based stereo
(d) Matching the reconstructed 3D structure with a shape model of the panel

When HRP-2 detects the corner of the panel in front of the panel end, the image processing is the same in principle. The grasping point was detected to within an error of 2*mm* and stably carrying a panel was accomplished.

7. SUMMARY

This presentation describes a vision system on a humanoid robot applied to constructing a terrapin hut. In response to design of the robot, a lightweight trinocular stereo camera system having auto shutter speed control was developed. An image processing software was implemented on OpenHRP, which was a software platform for humanoid robots. Calibration methods for distortion corrections were developed. Finally we demonstrated measuring a ground displacement, approaching a storage site of panels and grasping a panel.

ACKNOWLEDGMENTS

We express our thanks to the stuffs in AIST, Kawada Industries, Inc. and Yaskawa Electric Co., who cooperated with this R&D.

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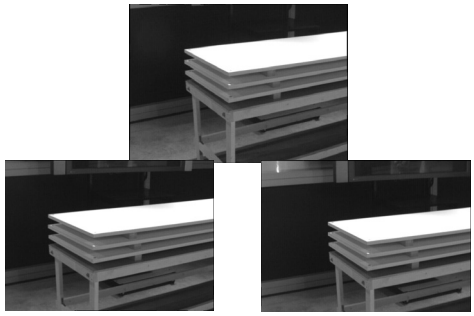
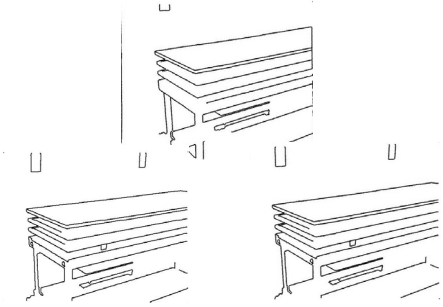
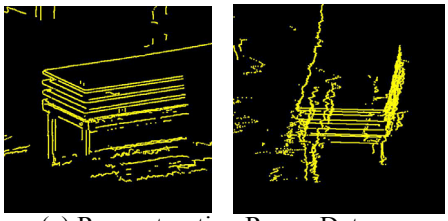


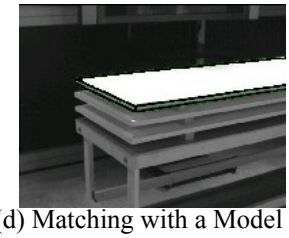
(a) Capturing Images



(b) Extracting Edge Lines



(c) Reconstructing Range Data



(d) Matching with a Model

Fig. 14. Detecting Panel

DEVELOPMENTS WITH THE NIST AUTOMATED CONSTRUCTION TESTBED

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Abstract: The NIST Construction Metrology and Automation Group is researching structural steel pick-and-place operations using a robotic crane coupled with sensor data distribution and construction component identification and tracking systems. This paper outlines new developments in this research including the addition of an automated gripper mechanism for RoboCrane and 4D-CAD sequenced multi-component placement. In addition, initial efforts to incorporate high-resolution scanning LADAR (Laser Detection and Ranging) data for world modeling and high frame-rate flash LADAR data for obstacle avoidance are discussed.

Keywords: construction automation, laser tracking, LADAR imaging, robotic crane

1. INTRODUCTION

The NIST Construction Metrology and Automation Group (CMAG) is conducting ongoing research to provide standards, methodologies, and performance metrics that will assist the development of advanced systems to automate construction tasks. Initial efforts in this research project have focused on autonomous large-scale pick-and-place operations using the assembly of structural steel as a test operation. Earlier work involved the integration of a laser-based site measurement system (SMS) with the NIST RoboCrane (TETRA Configuration) for autonomous 6 DOF control and docking of an I-beam payload using ATLSS connectors [1],[2]. Recent developments in this effort include design and construction of a mechanism for grasping I-beams, hardware and software upgrades for providing laser-tracking data, and the scripting of event tasks from a commercial-off-the-shelf (COTS) 4D-CAD package.

This paper describes the above recent developments and provides information regarding future research efforts to incorporate high-resolution LADAR systems for pose determination of target objects, and low-resolution, high frame-rate LADAR systems for obstacle avoidance and docking guidance.

2. RECENT EFFORTS

It is envisioned that a supervisor manning the Automated Construction Testbed (ACT) control station should be able to review a planned build sequence based on model data, and then command the robotic crane to execute the simulated sequence. In order to realize that scenario several items had to be developed. These included an automated gripper mechanism, a new Position Server middleware application to interface between the SMS and the RoboCrane controller, and a 4D-CAD front-end to provide a simulated assembly sequence.

2.1 The Automated Gripper Mechanism

The task of automating the steel beam pick-and-place operation required a mechanism to automatically grasp the target I-beam. The development of an automated gripper mechanism (AGM) is presented in this section.

2.1.1 AGM Design Goals

Two goals were considered during the design phase of the AGM. The primary goal was to provide a means to couple, manipulate, and release structural steel beams reliably and safely. The secondary goal was to enable controlled rotation of the beam ± 90º in yaw with ± 1º of resolution.

2.1.2 AGM Design Requirements

Seventeen functional requirements guided the AGM conceptual design phase. These requirements are outlined in the list below:

- Grip small structural I-beams of standard sizes between 12.7 cm (5”) and 20.3 cm (8”) wide.
- Lift beams with a weight of up to 453.6 kg (1,000 lbs).
- Secure the beam through roll and pitch angles of ±15º.
- Use the electrical power available on RoboCrane (480 VAC, 110 VAC and various VDC sources).
- Easily attach and detach from RoboCrane.
- Provide feedback to the controller that the beam has been gripped and secured.
- Keep beam secure if a power failure occurs while RoboCrane is in operation.
- Fit within the RoboCrane platform's footprint.

- Not to exceed 0.5 m in height.
- Service life of 2 years with light duty use indoors.
- Provide beam position resolution of 1 mm in RoboCrane's x, y, and z axes.
- Provide beam angular resolution of 1° in RoboCrane's roll, pitch, and yaw axes.
- Require a minimal number of mechanical and electrical parts.
- Must not weigh more than 45.4 kg (100 lbs) total.
- Grip and release the beam in 10 seconds or less.
- Be scaleable to handle 4,535.9 kg (10,000 lbs) beams.
- Principally use off-the-shelf parts wherever possible.

2.1.3 AGM Design

The AGM underwent a rigorous design process during which several alternatives were considered and rated based on the above requirements. The design that was selected (see Figure 1) consists of two manufacturing vises spaced 0.41 meters (16 inches) apart (along an I-beam's longitudinal axis) that are chain driven by a single motor. The entire assembly is attached to an aluminum frame, which is suspended from RoboCrane by 6 steel cables in order to provide vertical compliance (see Figure 2). Due to time and resource limitations the secondary goal of enabling controlled rotation of the beam was not pursued, but was assigned as a future-work task. This meant that beam rotation with the current AGM would be limited to RoboCrane's own yaw limits of ±30°.

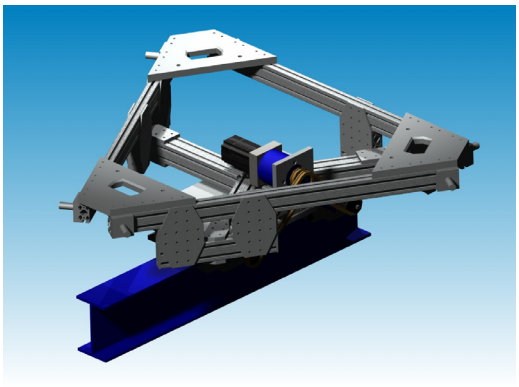

Figure 1: Rendering of Suspended Gripper Mechanism

Although the AGM was designed to be mounted either directly to RoboCrane or via the 6 adjustable-length, steel cables, attaching the AGM directly to RoboCrane does not provide any measure of safety when the robot is docking with a beam or a beam holder. If due to any number of possible positioning errors, the position of the robot ends up slightly lower or laterally offset than the commanded position when gripping a beam, the entire weight of the robot could end up resting on the beam or on parts of the gripper mechanism. This could damage the AGM, the robot, or the beam itself. Thus, the 6 steel cables were added as a means to provide a certain measure of mechanical compliance to the AGM when docking with a beam or when docking the beam with a holder. This way if the actual and commanded position of the robot differ, only the weight of the AGM will have to be carried by the beam or any of the AGM's exposed components.

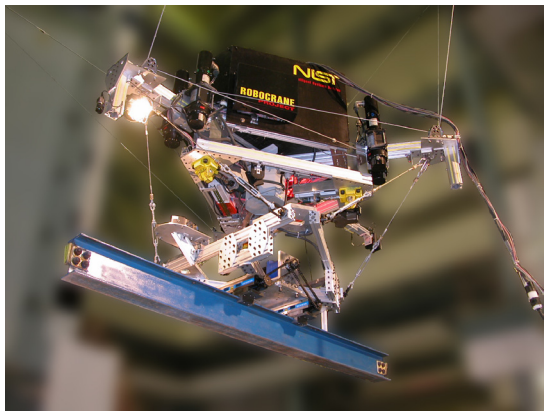

Figure 2: RoboCrane (Tetra Conf.) with Suspended AGM and I-Beam Payload

Figure 3 shows the two modified manufacturing vices mounted inverted to the AGM and coupled to the motor/gear reducer through the dual chain drive system.

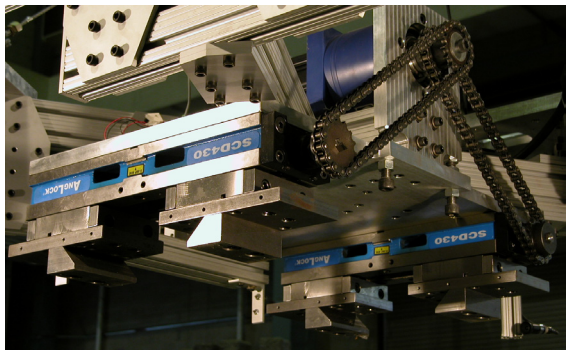

Figure 3: AGM Vice Mount and Dual Chain Drive System

Control of the AGM was achieved through software developed in the motor interface language provided by the manufacturer. This software is loaded on initial power-up of the motor, and requires only high-level commands (e.g. grasp, release) to be provided by the RoboCrane controller via an RS-485 communications link. Limit stops are provided by switches installed on the vices which signal the motor itself. A successful grasp cycle is determined by a combination of absolute vice position and motor torque value.

2.1.4 AGM Final Specifications

Safety: The vises on the AGM feature ACME lead screws, which are not back-drivable. Therefore, if the power fails while the beam is gripped, the weight of the beam cannot cause the vises to open. In addition, the AGM motor includes a built-in brake, which is set to automatically engage when the motor is stopped or when power to the motor is interrupted.

Gripping Size: The AGM is able to grip structural I-beams between 12.7 cm (5") and 20.3 cm (8") wide.

Grip/Release Speed: The AGM motor is capable of rotating at 3,000 RPM while driving the two vises via the chain drive. With the 1:10 gear reducer, the maximum rate of rotation of the gear head will be 300 RPM, or 5 revolutions per second. The vises require 31.5 revolutions in order to travel 66.7 mm (2.6") on either side (since these are self-centering vises). Therefore, the time required to open or close the jaws of the vises from fully closed to fully open (or vice versa) is 6.3 s.

Grip Force: In its final configuration, each of the two grippers on the AGM is able to produce approximately 10 kN (2200 lbf) of grip force. This grip force is sufficient to prevent an I-beam (with a mass of approximately 350 kg) from slipping out when it is gripped in a vertical orientation (i.e., at a 90º roll or pitch angle). Hence the grip force is more than adequate to secure a 453.6 kg (1000 lb) beam through roll and pitch angles of ±15º.

Weight: The AGM weighs approximately 136.4 kg (300 lbs), which is significantly more than the original specification of 45.4 kg (100 lbs). The initial specification may have been too ambitious and we found that meeting that weight limit and still being able to support a 453.6 kg (1,000 lbs) beam was not possible without adding significant cost and complexity to the design. However, considerable effort was made to keep the weight of the AGM to a minimum by using aluminum structural support wherever possible, while also using mostly off-the-shelf components.

Load Carrying Capacity: Due to the high weight of the as-built AGM, it is only able to lift beams with a mass of up to 318.2 kg (700 lbs) rather than the 453.6 kg (1,000 lbs) that was originally specified. This capacity is based on lift limitations of the specific configuration of RoboCrane used in our tests.

Feedback: The AGM provides feedback to the controller when the grippers have closed and when the correct torque has been applied through the motor interface software. In addition, two limit switches were fitted onto the vises to provide a stop signal once the vises have been fully opened. Finally, an onboard camera also provides visual feedback to the operator regarding the status of the AGM.

Dimensions: The AGM fits within the RoboCrane platform footprint and does not exceed 0.5 m in height when attached directly to RoboCrane. However, the AGM does exceed the 0.5 m height specification when attached by means of the 6 adjustable steel cables. Nevertheless, the added vertical compliance of the AGM when attached with the cables is necessary for safety purposes.

2.2 ACT Position Server

The SMS system is provided by the manufacturer with a software interface for managing laser transmitter setup, initial measurement frame calibration, and detector position monitoring. A NIST-developed Position Server accesses detector positions from the SMS interface and provides position and measurement quality data to the RoboCrane controller. The initial Position Server was a console application which managed the socket communications between the SMS interface and RoboCrane. The current Position Server now provides a GUI interface which displays real-time detector position data and status messages regarding system performance. Controls for the data communications stream and data logging are also provided. A screen capture of the Position Server is shown in Figure 4.

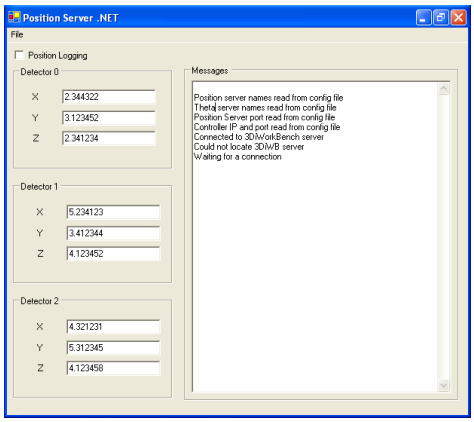

Figure 4: Position Server Screen Capture

In addition to software upgrades the detector hardware on RoboCrane has been modified. Initially, a PDA equipped with an 802.11b wireless network card was used with each detector to provide communications to the computer hosting the SMS interface and the Position Server. The PDA links were replaced with wireless serial LAN radios which improved data throughput and eliminated data loss resulting from the PDA's periodically dropping the connection. Overall data throughput increased, and position updates to the RoboCrane controller are now

available at approximately a 10 Hz data rate. Projected tracking software improvements should improve the data rate to approximately 20 Hz, enabling significant improvement in the motion control algorithms.

2.3 4D-CAD Interface

In order to provide an operator with a review of the planned build sequence, a COTS 4D-CAD package was integrated as a front-end to the ACT controller. Models of the holder and three I-beams used in the test structure were created and imported into the 4D-CAD package using VRML as a transfer format. The assembly sequence was then designated from within the 4D-CAD environment.

A parser program examines the 4D-CAD file, extracts the assembly sequence, and delivers a command script sequence to the RoboCrane controller for assembly of the test structure. Modifications to the assembled test structure (i.e. eliminating a beam from the assembly) can be accomplished from within the 4D-CAD system. However, the locations of the test structure's parts and their associated assembled positions cannot be modified from within the 4D-CAD system. Figure 4 shows a screen capture from the 4D-CAD system.

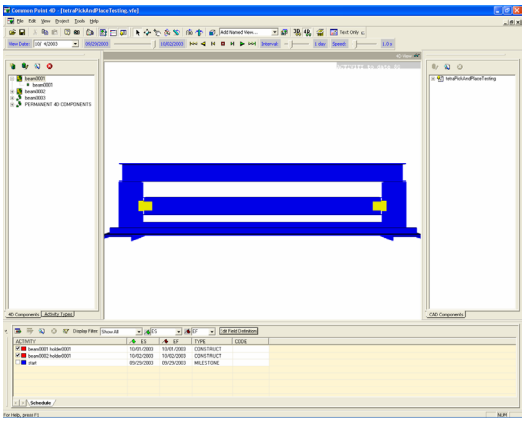

Figure 4: 4D-CAD Screenshot Showing Target Holder and Two Placed I-Beams

3. FUTURE WORK

In order to complete the autonomous pick-and-place operations, the location of all target objects must be known to the RoboCrane controller. In the current ACT configuration, locations of all components are known a priori based upon digitizing fiducial points on each of the objects using the SMS. Although some compliance is mechanically available through the suspended gripper mechanism and the ATLSS connectors, the assembly process is intolerant of positioning errors in either object location or the RoboCrane trajectory. As a result, objects in the assembly process must be carefully measured using the SMS digitizing system (human required) and no object movement is allowed following registration. To alleviate these restrictions, CMAG researchers are investigating the use of high resolution LADAR for pose determination of target objects and low resolution, high frame-rate LADAR mounted on RoboCrane for obstacle avoidance and docking control.

3.1 Locating Target I-Beams with High Resolution LADAR

Preliminary experiments demonstrated the feasibility of providing pose information from high resolution LADAR scans. Using a binning algorithm to segment the data set and then comparing the remaining data to a set of vertex points from a 3D model of the target beam, center mass position of a target I-beam was resolved to cm-level uncertainty and the z-axis rotation was found to within 0.1 of a degree. Details of the algorithm, experimental setup, and initial results can be found in [3]. Figures 5 and 6 show high resolution scans of the RoboCrane work environment.

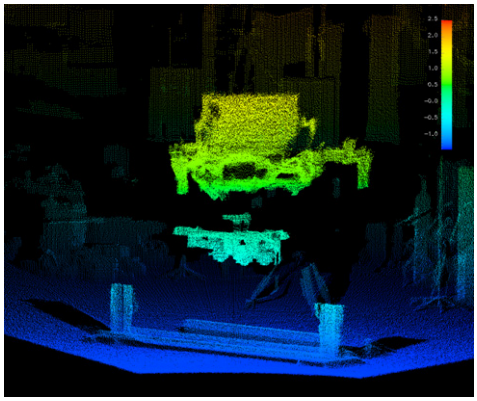

Figure 5: High-resolution LADAR Scan of RoboCrane and Target Structure.

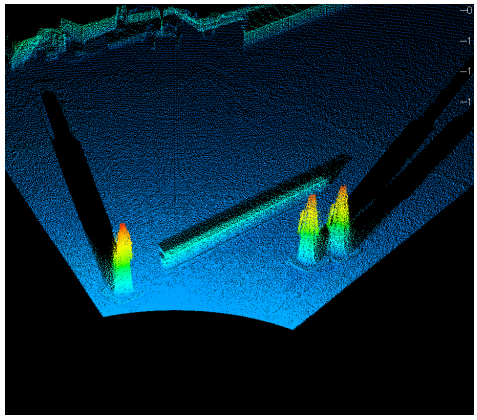

Figure 6: High-resolution LADAR Scan of I-Beam for Pick-Up (Safety Cones in Foreground)

3.2 High Frame-Rate LADAR for Obstacle Avoidance and Docking Control

Although initial tests indicated that pose data of target beams can be provided through high resolution LADAR scanning, the resulting pose information contains too high of an uncertainty for position-only crane guidance. In addition, the time required to capture and process a high-resolution scan is not suitable for real-time control, and therefore cannot accommodate changes in target beam location or appearance of new obstacles in the work volume. To overcome these limitations, the robot manipulator must be equipped with a means of perceiving its environment in real time.

CMAG researchers are investigating the use of a high-frame rate (approximately 30 Hz) low-resolution (160 pixels x 124 pixels) 3D optical range camera for obstacle avoidance and docking guidance. Details of the 3D range camera technology are provided in [4]. Figure 7 depicts a rendering of the range camera on RoboCrane during a docking sequence. Figure 8 shows range data obtained during a simulated docking approach. Figure 9 is a still video image from a separate camera recording of the simulated docking approach provided for a visual reference.

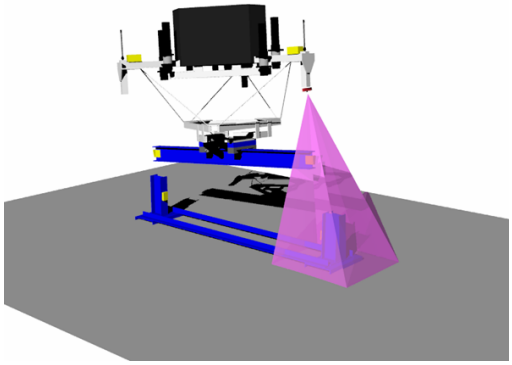

Figure 7: Rendering of RoboCrane Using LADAR for Docking Guidance

4. CONCLUSIONS

The NIST Construction Metrology and Automation Group is conducting ongoing research to provide standards, methodologies, and performance metrics that will assist the development of advanced systems to automate construction tasks. Recent development efforts in this research project demonstrated autonomous assembly of a multi-component test steel structure using a robotic crane with pose tracking provided by a laser-based site measurement system and assembly scripts generated from a COTS 4D-CAD package. Future efforts will incorporate LADAR scanning to eliminate the need for manual measurement of object locations and to provide greater sensing capability and autonomy for the robotic crane.

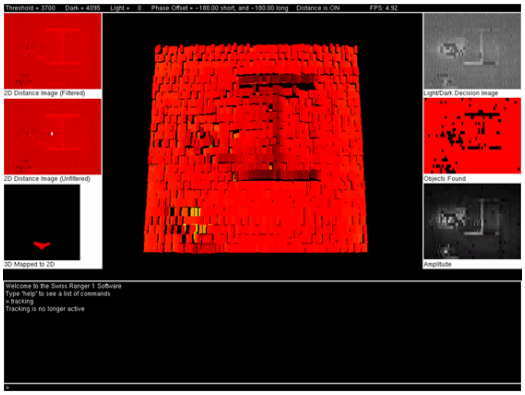

Figure 8: Range Data from a Simulated Docking Approach

Figure 9: Video Still from a Simulated Docking Approach

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SIMULTANEOUS OBSTACLE DETECTION FOR MOBILE ROBOTS AND ITS LOCALIZATION FOR AUTOMATIC BATTERY RECHARGING

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Abstract: In this paper, we will research the simultaneous performing of both the obstacle detection for mobile robots and the localization for automatic battery recharging. And also, this research suggests the new-concept of sensor system using the ultrasonic devices for performing the above mentioned tasks. Robots with this new sensor system can not only easily detect the obstacles when moving, but also know their own relative position to the recharging station. For the performance verification, the proposed system will be applied to the home service robot, called 'HOMBOT II' which was developed by Intelligence Robotics Research Center at KIST(Korea Institute of Science and Technology).

Keywords : Obstacle detection, Localization, Mobile robot

1. INTRODUCTION

The powerful and long-last power system for mobile robots is needed to perform the given tasks smoothly and perfectly. Unfortunately, there are the limitations of battery technology. And also, when we use the recharging system, the recharging battery should be replaced and recharged manually by human being. So, many autonomous recharging systems of mobile robots have been developed to solve these problems. In this paper, the localization system using the existent ultrasonic system implemented in 'Hombot II' for the obstacle detection is suggested to perform the docking task to the station for the automatic recharging. Robot with the suggested new sensing system can have not only the ability to detect the obstacle but also to estimate its relative position to the station. The suggested sensing system has a merit in the aspect of the cost comparison with other sensing systems for the localization because it uses just the ultrasonic sensor.

2. THE OBSTACLE DETECTION

2.1 The basic concept and structure of the obstacle detection system

Hombot has already been equipped with the 12 us(ultrasonic) modules in the front, the back side, the right side and the left side for the obstacle detection (**Figure 1**). While moving, Hombot can detect the obstacles using the 12 us modules. To avoid the cross-talks between modules, the 12 us modules are divided into the 4 groups, and then the 4 groups consecutively carry out their ultrasonic emitting and receiving task.

Figure 1. Hombot and the us modules' configuration

The obstacle detection system is composed of the main control board and 12 us modules (**Figure 2**). The main control board caculates distances between us modules and obstacles through the ultrasonic transimitting and receiving operation, and then transmits the distance data to the main computer of hombot using the CAN-based communication.

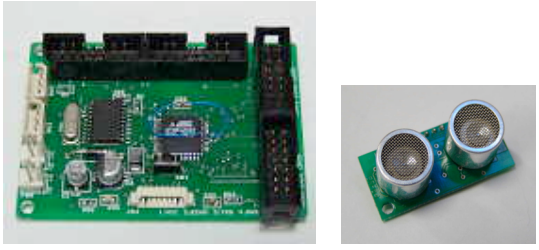


Figure 2. the main control board and the us module

2.2 The distance measurement using us modules

The main control board of Hombot sends the trigger pulse into the us module, and then the us module emits the ultrasonic bursts and waits for the reflected ultrasonic. If us module receives the reflected signal, us module sends the echo pulse signal for the us reception into the main control board. That is, if the us modules gets the trigger pulse from the main control board, it pulls up the level of the echo pulse output to be ready to receive the reflected ultrasonic. Then, when the reflected ultrasonic signal is received, the level of the echo pulse output is pulled down. The distance could be measured by using two time points at which the signal level of the echo pulse output is pulled up and pulled down with considering the speed of sound in air. **Figure 3** illustrates the operating principle of the us module.

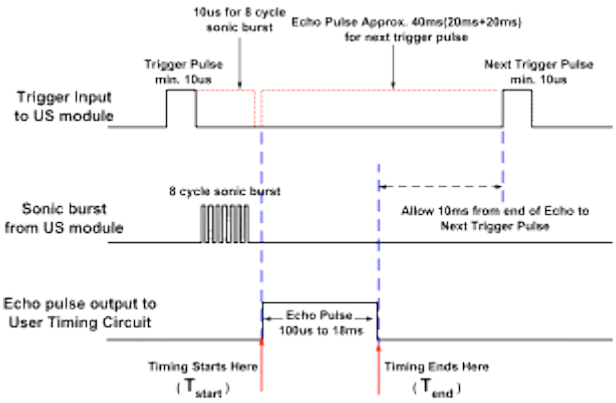


Figure 3. the operating principle of the us module

3. THE LOCALIZATION SYSTEM

3.1 The basic concept of the localization system

The localization system is developed by modifying the existing ultrasonic system for the obstacle detection. The main purpose of this research is to develop the integrated system which is capable of the obstacle detection and the localization of robot just using the ultrasonic sensor without any other additional sensors. **Figure 4** shows the localization of robot. Both receivers of us module #0 and #2 of Hombot receive the ultrasonic signals emitted sequentially from two transmitters of the external station. After that, the localization system gets the four distance data. Using the four distance data - Dist at #0 from Tx1, Dist at #1 form Tx1, Dist at #0 from Tx2 and Dist at #1 from Tx2, the relative coordinates of two receivers of us module #0 and #2 of Hombot can be calculated.

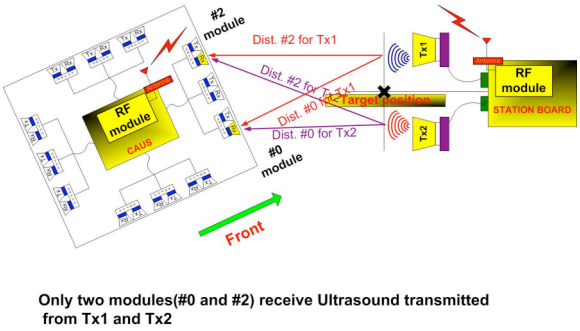


Figure 4. the localization system

3.2 The composition of the localization system and the calculation of the position

(1) The main control board for Hombot

The main control borrad (**Figure 5**) enables Hombot both basically to detect the obstacles while moving and to estimate the relative position of Hombot to the station. And it transfers the modes of us modules according to the kind of operation which is the obstacle detection or the localization. When Hombot operates the obstacle detection, the main control board uses the us modules as the mode of us transmission-recption. On the other hand, when Hombot operates the localization, the us module is changed into the mode of us reception only.
The main control board has the RF module to communicate with the station, and it uses the CAN based communication with the main computer of Hombot.

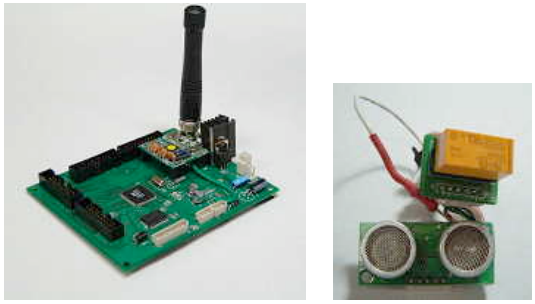


Figure 5. the main control board for Hombot and the modified us module

(2) The modified us module

The us modules is modified to be suitable for the mode change. **Figure 6** is the schematic diagram of the revised transmission part of us module. In the modified system, handling the relay makes it posible to control for the transmission part of us module to be turned on or off. If the transmitter of us module is off for the mode of localization, the us module just

can be ready to receive the externally emitted ultrasonic. On the other hand, if the transmitter of the us module is on for the mode of obstacle detection, the us module can do not only transmitting us but also receiving us which is emitted by its own transmitter.

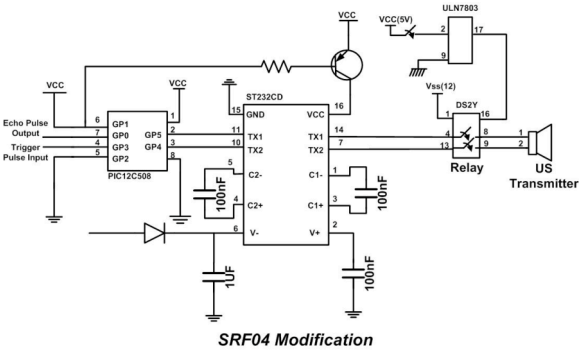


Figure 6. the schematic diagram of the modified us module

(3) The external us transmission system of the station

The external us transmisstion system for the station is composed of the us transmission control board and two us transmitters (**Figure 7**).

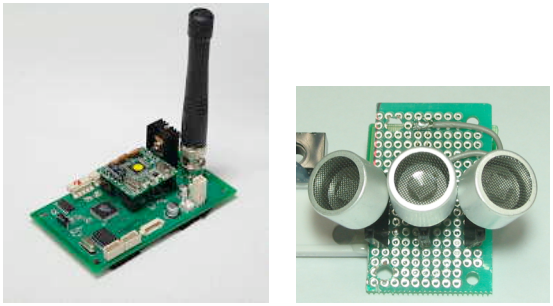


Figure 7. the external us transmission system

The us transmission control board chooses the method of us emission according to the kind of command transmitted from the main control board of Hombot through the RF communication.

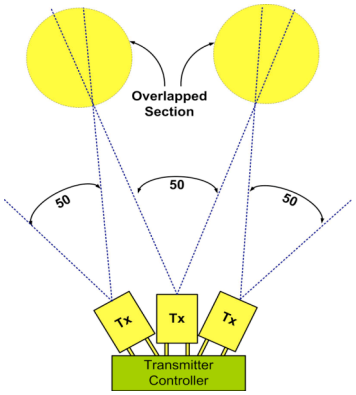


Figure 8. the extension of directivity

The us transmitter of the station emitts the 40kHz us and has the directivity of 50[deg.]. The us transmitter has to be modified like the right picture of **Figure 7** to expand the directivity in order to overcome the limitation of the angle of us transmission-reception owing to the small directivity of 50[deg.] (**Figure 8**).

(4) How to calculate the position of Hombot's receivers, Rx0 and Rx2.

The positions of two receivers, Rx0 and Rx2 of Hombot, can be calculated by using the equation of circle with the four distance data (**Figure 9**).

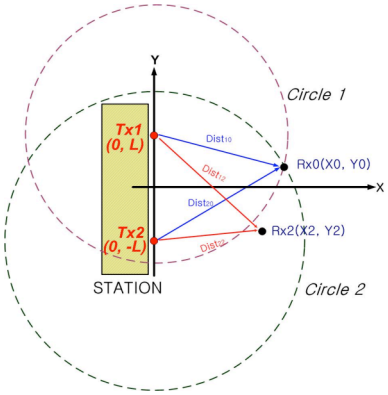


Figure 9. Getting positions using the equation of circle.

$$X0 = \sqrt{Dist_{10}^{\ 2} - (y-L)^2} = \sqrt{Dist_{20}^{\ 2} - (y+L)^2} \quad (1)$$

$$Y0 = \frac{Dist_{10}^{\ 2} - Dist_{20}^{\ 2}}{-4L} \quad (2)$$

$$X2 = \sqrt{Dist_{12}^{\ 2} - (y-L)^2} = \sqrt{Dist_{22}^{\ 2} - (y+L)^2} \quad (3)$$

$$Y2 = \frac{Dist_{12}^{\ 2} - Dist_{22}^{\ 2}}{-4L} \quad (4)$$

The coordinates of two receivers are the above formulas (1), (2), (3) and (4).

4. TIME SYNCHRONIZATION

The start time of us reception of Hombot(=t1) has to coincide with the us transmission time of the station(=t2) in order to get the exact distance data between Hombot and the station. The method to coincide t1 with t2 is named 'time synchronization'. There are no ways for Hombot to communicate with station except for RF communication. And there is

the fixed delay time between Hombot's RF module and station's RF module when the transmited RF packet from Hombot is received to the RF module of the station. However the process time of RF packet computed by the micro-processor of station's control board is not fixed but always varied. Thus, Hombot successively transmits two RF packets, '**the command packet'** and '**the sync Packet**'. The command packet means the us transmission method of the station. The sync packet is actually used for time synchronization. The station understands the meaning of the first RF packet (the command packet) through processing the command packet using the micro-processor. After the enough processing time of the command packet, which is experimentally selected and fixed, the station is ready to receive the second RF packet (the sync packet). The sync packet through the RF module of the station is transmitted not to the micro-processor, but to the simple circuit of the control board of the station (**Figure 10**).

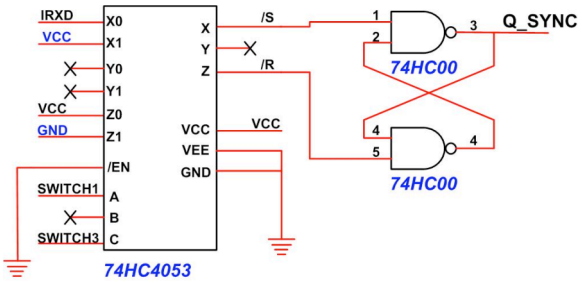


Figure 10. the circuit for capturing the sync packet

After the enough processing time for the command packet, the signal line of RF packet is connected to the input pin (IRXD) of the multiplexer 74HC4053 instead of the micro-processor of the station.

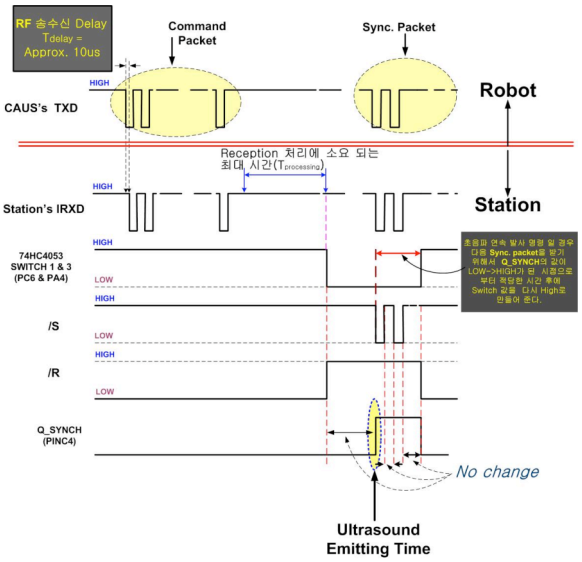


Figure 11. the timing diagram for the time sync.

Thus, if the station's control borrad receives the sync packet through the RF module, it can capture the exact time at which the sync packet is transmitted to the input pin(IRXD) of the above circuit. When the sync packet enters the input pin(IRXD), the level of 'Q_SYNC' changes 'Low' into 'High'. The fixed delay time for the RF communication can be compensted because the communication time between two RF modules is fixed. If the fixed delay time is compensated, the us transmission start time can be synchronized with the us reception start time of Hombot by capturing the time point at which the level of 'Q_SYNC' changes 'Low' into 'High'. **Figure 11** is a timing diagram for the time synchronization.

4. THE EXPERIMENT AND RESULT

The localization system is taken into Hombot, and then the performance of the localization system has been tested using a GUI developed for various experiments (**Figure 12**).

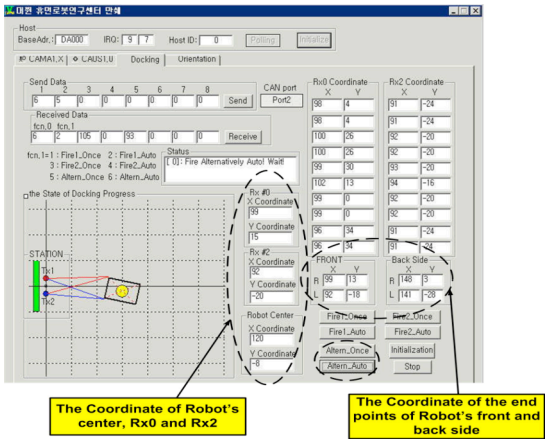


Figure 12. the GUI for the localization

The relative position of Hombot to the station has been estimated through the GUI after positioning Hombot like **Figure 13**.

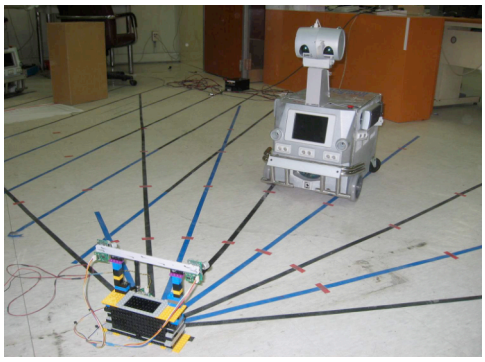


Figure 13. the experimental circumstance

The measured positon by the localization system has been compared with the real position acquired by the 3-D coordinate mearsuing equipment named 'Flash point' (**Figure 14**).

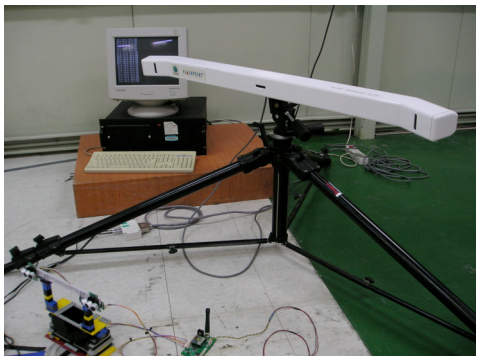
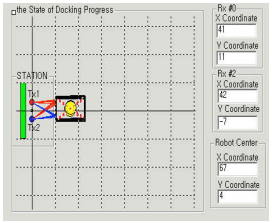
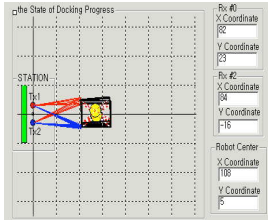


Figure 14. Flash point

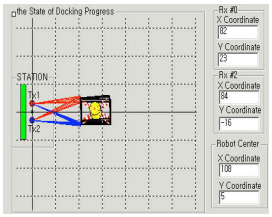
In our experimental results, the average of error was incresed as much as Hombot becomes more distant from the station (**Figure 15**). The reason may arise from the fact that we have used the fixed value of velocity about the ultrasonic signal (340m/s) while it could be affected by the external conditions of environment such as air pressure, humidity, temperature and so on.



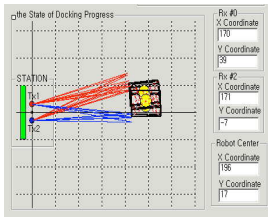
50cm



100cm



150cm



200cm

Distance	50cm	100cm	150cm	200cm
The aver. error	4.5cm	8.6cm	19.4cm	27.2cm

Figure 15. the result of localization for the distance

And also, though the us transmitter is modified to overcome the limitation of us directivity, there still exists the range of angle at which the localization can not be achieved, the angles over 45° on the basis of the centered line with the distance of 50cm from the station. And the intensity of us emission has the difference according to the angle (**Figure 16**). The difference of intensity can also affect the precision of localization.

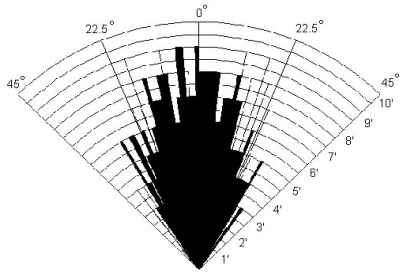


Figure 16. the intensity pattern of the us transmitter

5. THE CONCLUSION

Hombot already has the ultrasonic system for the obstacle detection. The existing ultrasonic system is modified to develop the localization system with the obstacle detection for practical use. The new ultrasonic system simultaneously have two functions of the obstacle detection and the localization. That is, the mode of the ultrasonic system can be changed according to the main purpose which is to detect the obstacle or to estimate the relative position of robot. When localizing robot, the average of error between the real position and the measured position increases as much as the robot is put more and more distance from the station. And there still exists the range of angle at which robot can not estimate its own position despite of modifying the us transmitter for overcoming the limitation of us directivity. In advance, the further study to overcome the weak points of ultrasonic system such as the directivity, the difference of intensity and so on is needed to enhance the performance of the suggested system. Moreover, the real docking needs to be experimented using the localization system.

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RELIABLE DETECTION OF SOUND'S DIRECTION FOR ACTIVE AUDITION

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Abstract: In this paper, we propose reliable detection of sound's direction for human robot interaction. Compared with previous researches, this system comprises simpler algorithm and a proposed nonlinear amplifier which has advantages to increase a detectible distance of sound signal in spite of simple circuits. Moreover, we propose the new performance index using cross-correlation to make reliable detection of sound's direction. Also, since this system include a function to detect a period of voice signals, the robot can know when to start finding sound's direction and performing speech recognition automatically. In order to verify our system's performances, we install the proposed audition system to the prototype robot, called IROBAA (Intelligent ROBot for Active Audition), and describe the experimental results.

Keywords : sound localization, voice activity detection, human robot interaction, intelligent robot

1. INTRODUCTION

The speech recognition has been applied into various systems and its performance has been improved greatly. In addition to the recognition, sound localization becomes a technology of much interest in the research field of human-robot interaction. In order to recognize speech with high confidence, the techniques which separate speech from various sound and remove noise from the signal of speech have been received a great deal of attention. Also, humanoid robots integrated with computer vision and various sensors have been developed for similar behaviors of human [1]-[10].

The objective of this research is to develop the techniques which enable the following scenario. Our robot recognizes its name and the direction of sound as well when a man calls. Then it turns its face to the direction, and can possibly recognize the person through face recognition technique to communicate with him.

We use nonlinear amplification as a preprocessor in order that speech recognition system can recognize speech at a long distance robustly against noises in the environment. Furthermore, to make reliable detection of sound's direction, we propose a new performance index using differences of cross-correlation. Also, since this system includes a function of VAD (Voice Activity Detection), the robot can know when to start finding the direction and performing speech recognition automatically.

To verify our system's feasibility, the proposed audition system is installed in the prototype robot, called IROBAA (Intelligent ROBot for Active Audition), which has been developed at the KIST (Korea Institute of Science and Technology).

Fig. 1 shows the audition system installed in IROBAA. The audition system is composed of pre-amplifier board, mic-mounted circle pad, commercial AD converter, and a notebook computer to execute our program. The AD converter samples data from three microphones to the rate of 11 kHz for each.

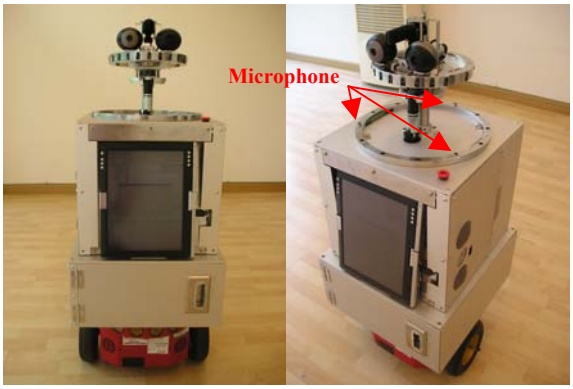

Figure 1. Active audition system installed in IROBAA.

2. Audition System of IROBAA

Nonlinear amplification which is able to make dynamically variable amplification according to the signal magnitude is required to increase the range of detectable distance. If the ratio of amplification is fixed to small one, the signal of speech occurring at the long distance can be hardly extracted from its received signal whose magnitude is small enough for the contents of speech to be canceled by noise. To the contrary, with large ratio, the signal occurring nearby sometimes may be saturated in the AD conversion. For this reason, the speech recognition system which

is less affected by the distance to sound's source is necessary. To resolve this problem, we propose the use of SSM2166, made by Analog Device Corporation, which enables the nonlinear amplification. Our circuit, as shown in Fig. 2, is adjusted to compression ratio of 5:1.

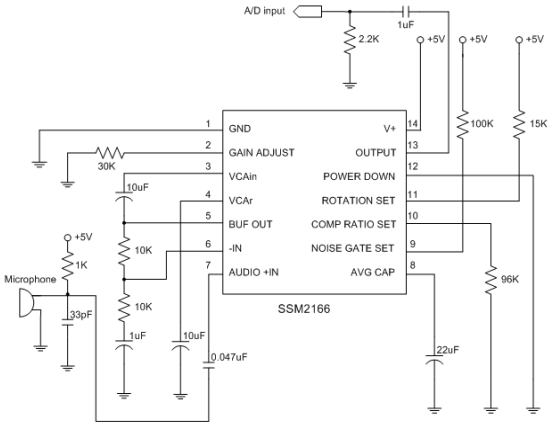

Figure 2. Circuit of Nonlinear Pre-Amp

In order to verify our nonlinear amplifier's performance, we should perform experiments to compare with normal linear amplifier. In the Figs. 3 and 4, the left hand shows sampled signals amplified by linear amplifier and the right hand shows sampled signals amplified by proposed nonlinear amplifier. Every source of speech signals is the same. Besides, main computer performs normalization within a range of ± 0.5V so that they are suited to speech recognition.

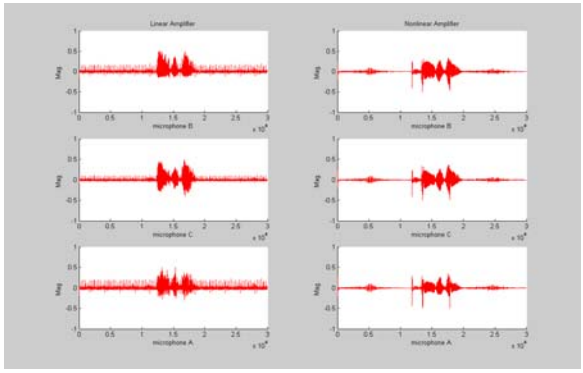

Figure 3. Compared two data of a distance of 0.5m

Fig. 3 shows speech signals outputted at 0.5m distance. This figure shows that linear signals are more noise and unclear shape than nonlinear signals.

Fig. 4 shows speech signals outputted at 1.5m distance. This figure shows that because the linearly amplified signals (left) are far smaller than nonlinearly amplified signals (right), they can be canceled with noise signal. Ultimately, as a pre-amplifier board is made with a proposed nonlinear circuit, we can get advantages to increase a detectable distance of sound signal and to reduce calculation time so as to execute various filtering algorithms such as low or high pass filtering.

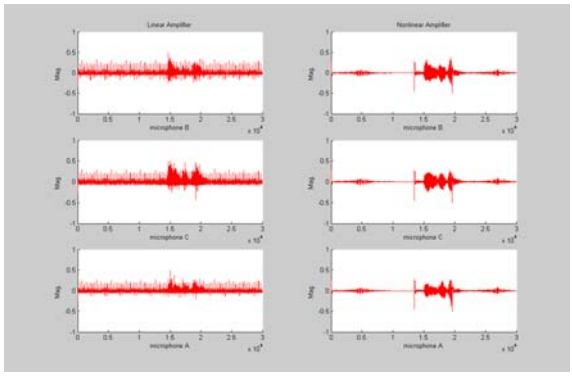

Figure 4. Compared two data of a distance of 1.5m

3. Tracking of Sound's Direction

This paper uses DOA (Delay Of Arrival) for tracking the direction of sound [6]-[10]. DOA is the method that uses a time-delay from the source of sound to each microphone. Even though the time delay is short, the difference of arrival time occurs between array-shaped microphones. In Fig. 5, three microphones are arranged such that their distances from the center of triangular rod are the same. Two couples of A vs. C and B vs. C are selected in the view point of C. Note that the sampling data has maximum delay of time when a sound enters straightly through both A and C, or B and C.

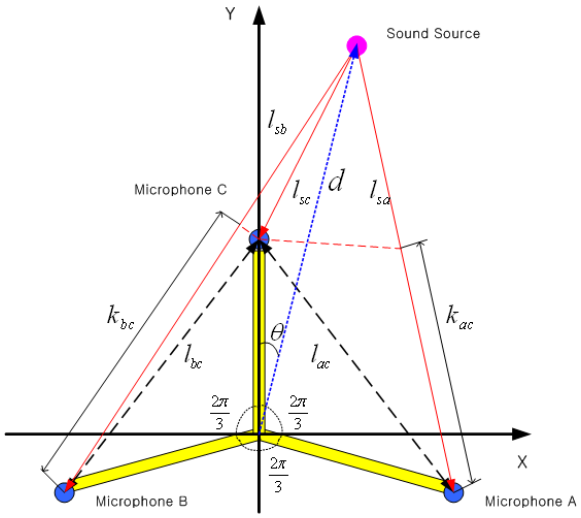

Figure 5. Location of three mirophones

In this case, the relative distance corresponding to the maximum delay is defined as l_{ac} (or l_{bc}). Also, the distance between sound's source and mic. A (mic. C) is defined as l_{sa} (or l_{sc}). The velocity of sound and sampling frequency are defined as v and F_s

respectively. The number of sampling about the maximum delay is defined by (1) and (2) where n_{ac} is the number of sampling of maximum delay between A vs. C microphone and n_{bc} is the other one between B vs. C microphone.

$$n_{ac} = \frac{l_{ac}}{v} F_s \tag{1}$$

$$n_{bc} = \frac{l_{bc}}{v} F_s \tag{2}$$

The relation coefficient between mic. C and mic. A is defined by (3). Also, The relation coefficient between mic. C and mic. B is defined by (4). The variable t_g is a target number of delay in the g^{th} sampling period. Equation (3) and (4) is considered by sampling data from g=0 to g=∞. However, the real application of infinite period is impossible. Therefore, variable t_g is determined by suitable sampling data. We should decide the optimal sampling period consisted of 552 samples through experiments.

$$R_{ac}(k) = \frac{\sum_{g=0}^{\infty} \{A(t_g - k)C(t_g)\}}{\sqrt{\sum_{g=0}^{\infty} A(t_g - k)^2} \sqrt{\sum_{g=0}^{\infty} C(t_g)^2}} \tag{3}$$

$$R_{bc}(k) = \frac{\sum_{g=0}^{\infty} \{B(t_g - k)C(t_g)\}}{\sqrt{\sum_{g=0}^{\infty} B(t_g - k)^2} \sqrt{\sum_{g=0}^{\infty} C(t_g)^2}} \tag{4}$$

The variable k represents the number of actual delay samples. The number of delay k, in our configuration, spans to the range of $-n_{ac} \sim n_{ac}$ in this (3) and $-n_{bc} \sim n_{bc}$ in this (4) where its positive/negative value means that the sound enters microphone A and B earlier/later than microphone C.

Now, sound's direction should be calculated using relation coefficient R_{ac} and R_{bc} for all possible k_{ac} and k_{bc}. Fig. 5 illustrates the number of delay samples and the actual angle of sound's direction. An actual delay of sound's direction is expressed as (5) and (6).

$$k_{ac} = \frac{(l_{sc} - l_{sa})}{v} F_s \tag{5}$$

$$k_{bc} = \frac{(l_{sc} - l_{sb})}{v} F_s \tag{6}$$

However, we can't know the location of sound source (θ , d) yet. Therefore, the following method is proposed to estimate the sound source location. Matrix r presents the cross correlation of R_{ac} and R_{bc} for all possible k_{ac} and k_{bc}. All values of matrix r are calculated by (7).

$$r(\theta) = R_{ac}[k_{ac}(\theta)] \cdot R_{bc}[k_{bc}(\theta)]$$
$$\text{where } 1° \le \theta \le 360° \text{ i.e. } \theta = 1°, 2°, ..., 360° \tag{7}$$

Next, because we want to find the angle of sound's direction, we should first know the maximum value in the matrix r. After we fix threshold value in the r by using (8), we perform normalization to the r by using (9).

$$r_{thr} = 0.99 \times \max\{r(\theta)\}$$
$$\text{where } 1° \le \theta \le 360° \text{ i.e. } \theta = 1°, 2°, ..., 360° \tag{8}$$

$$r(\theta) = 0 \ \ if \ r(\theta) < r_{thr}$$
$$\frac{(r(\theta) - r_{thr})}{(r_{\max} - r_{thr})} \ \ if \ r(\theta) \ge r_{thr}$$
$$\text{where } 1° \le \theta \le 360° \text{ i.e. } \theta = 1°, 2°, ..., 360° \tag{9}$$

And, if we perform a weighted average to the r by using (10), we will find the angle of sound's direction.

$$\frac{\sum_{\theta=1}^{360} (r(\theta) \times \theta)}{\sum_{\theta=1}^{360} r(\theta)} = \theta_{sd} \tag{10}$$

4. Reliable Detection of Sound's Direction

In a real speech signal, as there are reverberations, noise signals and consonants which have weakly periodic signals, wrong detections of sound's directions are calculated by computer frequently. Therefore, in order to find accurate directions of speech signal, we should detect sound's direction at the frame which has maximum energy within a period of speech signal.

The energy of a frame is expressed as (11).

$$E_{frame} = \frac{1}{k} \sum_{i=0}^{k} x^2(i) \tag{11}$$

The $x(i)$ is a sampling data of i-th in speech signals.

However, a method using frame energy has several problems. First, if much noise is included in a speech signal, it will be able to select a frame which is not a period of speech signal. Second, because the frame having a maximum energy has not always good data to find an accurate direction of sound, accuracy related to detecting sound's direction can be reduced.

To fix these problems, we propose a new performance index rather than the frame energy. Given each frame, the performance index is expressed as (12).

$$P = r_{\max} - r_{\min} \tag{12}$$

We've found a notable feature through lots of experimental investigation: it is true that when we spread values calculated by using (7) on the range of all angles, the difference between magnitudes of the cross-correlation is very informative to find reliable detection of sound's direction. After selecting the reference frame having the maximum value of our performance index P in a sample period, we decide direction whose cross-correlation value is the maximum at the selected frame as the final result.

To compare a frame energy method with a cross-correlation method, we used three commands such as "go to a living room," "go to a big room," and "patrol my home." Generating spots of each command were total 13 points at a distance of 1 meter. The azimuth which ranges from -90° to 90° was divided by every 15°. Table I is the average of experimental results.

Table I. Compare frame energy with proposed index

	Successful detection of sound's direction		Angle error of sound's direction	
Method	Frame Energy	Proposed	Frame Energy	Proposed
Average	82%	97%	7.2°	5.9°

As you see Table I, the cross-correlation method is better in the percentage of successful detection and average of angle error than the frame energy method. Figure 6 illustrates a 3 dimension graph which consists of numerical values calculated by using (7). At this time, used speech command is "patrol my home" coming at a distance of 1 meter and 30°. Where a frame has the proposed performance index which have the largest value throughout all the frames (See the inside of blue circle in Fig. 6), we can find an accurate direction of sound.

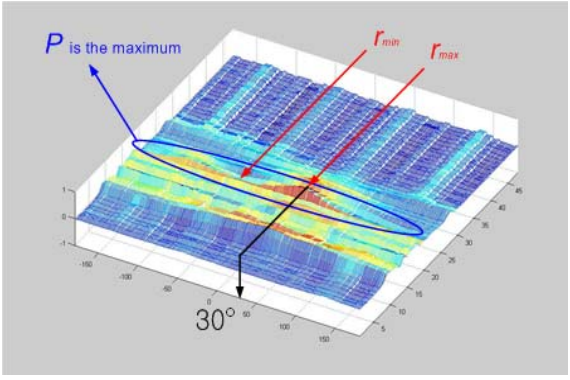

Figure 6. The 3D graph of cross-correlation

5. Voice Activity Detection

For the purpose of effective interaction between human being and a robot, it is necessary to extract the period in which only voice signals are included: Non-voice or silent periods are unnecessary or harmful. Therefore, we propose a function of VAD (Voice Activity Detection) using autocorrelation method to find pitch information. IROBAA executes a reliable detection of sound's direction and speech recognition when the robot is decided to detect signals of voice by VAD method. Pitch information rather than energy is applied to the VAD since the former has the advantage of a robust feature against noises [11][12]. Beside, In order to detect a pitch, we use an autocorrelation method which is composed of simpler algorithm instead of FFT.

The frequency of a vocal cord concerning human being exists in the range between 50 and 250Hz in case of a male and between 120 and 500Hz in case of a female. Therefore, if we put 552 samples per one frame into the autocorrelation equation, the executed signal will show pitch having periodic form of human vocal cord. The equation of the autocorrelation is expressed as (13).

$$R_{cc}(k) = \frac{\sum_{g=0}^{600}\{C(t_g - k)C(t_g)\}}{\sqrt{\sum_{g=0}^{600} C(t_g - k)^2}\sqrt{\sum_{g=0}^{600} C(t_g)^2}} \tag{13}$$

Then, after we perform a medium filter which has excellent features in removing impulse noise, edge signal preservation and smoothing, we can calculate differential values about autocorrelation results. In case of real voice signals, since magnitude of a periodic form and differential values between sampled signals is large, the peak values can be calculated by applying threshold value to differential values.

Finally, as we can know the number of samples between two peak signals, the pitch can be detected by (14). To improve accuracy of VAD, we should also detect the second pitch in a frame.

$$Pitch = \frac{\text{Sampling Frequency}}{\text{A number of samlpes between the two peaks}} \tag{14}$$

Now, after making weighted sum of the calculated pitches of 20 frames, we can infer extracting the period of voice signal.

Since the A/D converter which is installed in IROBAA has the function of double buffering, the robot can continuously execute the VAD algorithm at a second intervals without loss of raw data. Consequently, it can automatically and continuously perform finding direction of sound and speech

recognition whenever speech commands enter to microphones.

6. Speech Recognition System

For the purpose of human-robot interaction, it is necessary for performing speech recognition and synthesis as well as detection of sound's direction. IROBAA performs speech recognition using a commercial engine, however, with no additional mic. for the recognition only. To recognize speech reliably, we input pre-processed signal of speech to L&H engine. Fig. 7 shows the block diagram of the speech recognition system.

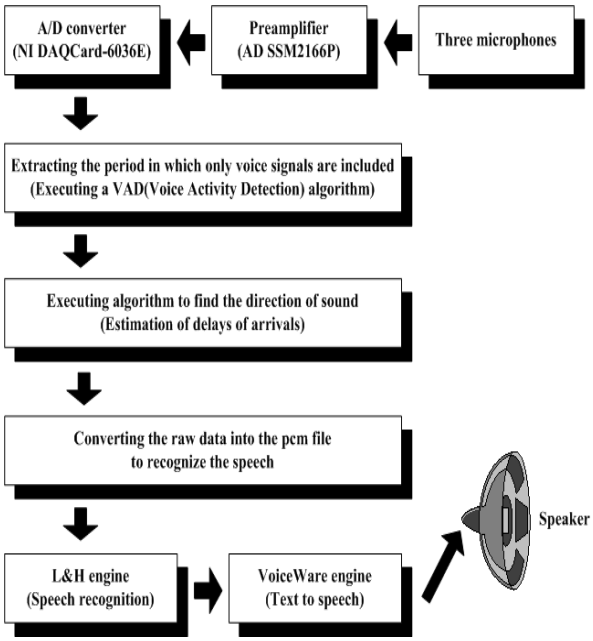

Figure 7. Block diagram of the speech recognition system

The speech synthesis of IROAA uses commercial speech synthesis engine which outputs the most natural speech through a speaker.

7. Experimental Results

Fig. 8 shows experiment setup. This experiment was conducted in an ordinary room, where background noise of about 55dB is generated by computer fans, an air-conditioner and motor noise in through the robot. Spots for sound's sources are total 24 points (See the red points in Fig. 8). The angle is divided by every 15° azimuth at a distance of 1 meter. The computer's speaker emits commands which were previously recorded in about 90dB volume. If the error of detected sound's direction is up to 30°, the result will be regarded as failure.

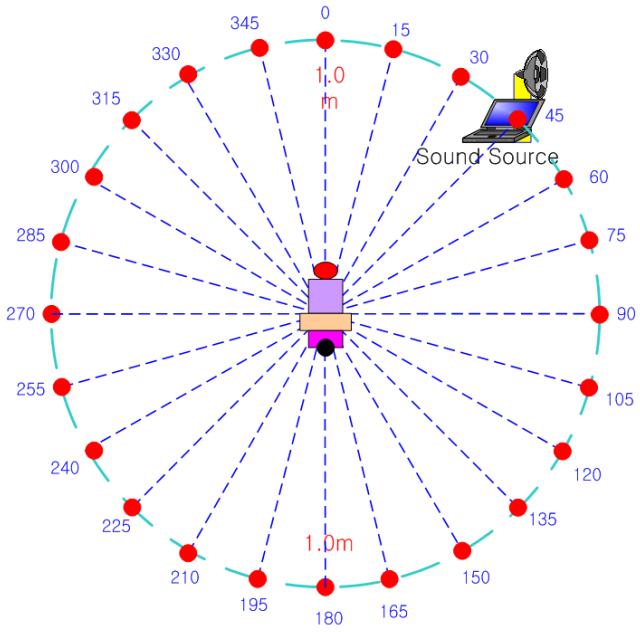

Figure 8. Experiment Setup

Table II is experimental results at 1m distance. Three commands are mostly used commands in IROBAA: "Go to a living room," "Go to a big room," and "Patrol my home."

Table II. The results of experiment at 1m distance

Command	Go to a living room		Go to a big room		Patrol my home	
Angle	recognition	direction	recognition	direction	recognition	direction
0°	FAIL	352°	FAIL	352°	FAIL	FAIL
15°	OK	13°	OK	352°	FAIL	13°
30°	OK	21°	OK	20°	OK	29°
45°	OK	36°	FAIL	44°	FAIL	43°
60°	FAIL	62°	OK	72°	OK	62°
75°	FAIL	83°	OK	76°	OK	76°
90°	OK	90°	OK	95°	FAIL	98°
105°	OK	104°	OK	108°	FAIL	104°
120°	OK	FAIL	OK	FAIL	FAIL	121°
135°	OK	FAIL	OK	138°	OK	FAIL
150°	OK	FAIL	OK	155°	FAIL	155°
165°	FAIL	165°	FAIL	165°	FAIL	165°
180°	OK	204°	OK	194°	FAIL	198°
195°	OK	199°	OK	199°	OK	199°
210°	OK	205°	OK	205°	OK	208°
225°	OK	221°	FAIL	227°	OK	201°
240°	FAIL	239°	FAIL	239°	OK	227°
255°	FAIL	260°	FAIL	256°	OK	256°
270°	OK	268°	FAIL	276°	OK	270°
285°	OK	FAIL	OK	280°	OK	280
300°	OK	304°	OK	288°	OK	304°
315°	FAIL	316°	FAIL	331°	OK	319°
330°	FAIL	331°	FAIL	331°	FAIL	331°
345°	OK	347°	OK	342°	FAIL	347°
Successful Average	Sound's Direction		Angle Error		Speech Recognition	
	90.3%		5.1°		59.7%	

This results show excellent performance at the short distance (1m): percentage of successful sound's direction is 90.3%. Moreover, the average of errors about the estimated sound's direction is 5.1° corresponding to three commands. However, percentage of successful speech recognition is not so good. This may result from the limited performance of speech recognition engine and the incompleteness in extracting exact period of voice from VAD. Therefore, we should analyze and improve the VAD algorithm to increase successful rate of speech recognition in the integrated system.

8. Conclusions

In this paper, conventional form of array-typed microphones is avoided. Also, simple and reliable algorithm with new pre-processing hardware is developed such that we are able to find the direction of sound's source from entire azimuth by using three microphones. Furthermore, it makes possible to perform speech recognition without another specific microphone (i.e., wireless or unidirectional sensitive microphone).

The audition system of IROBAA is designed for the optimized performance in the interaction between a human being and a robot. Consequently, this system has some distinguished functions. First, using the proposed pre-amplifier with simple circuits, we can get advantages to increase the detectible distance of sound's signal and to reduce noise. Second, tracking of sound source direction is often obstructed by echo sound due to surrounded obstacles. Moreover, as there are noise signals and consonants which have weakly periodic signals in the sampled speech signals, wrong detections of sound's directions may be calculated by computer frequently. In order to solve the problem, we proposed the new method to select the frame which has good information to find sounds direction (The fame is composed of 552 speech sampled data) based on cross-correlation. Third, as we apply VAD using autocorrelation, it can automatically and continuously perform finding direction of sound and speech recognition whenever speech commands enter to microphones. Finally, for the purpose of effective interaction between a human being and a robot, we have integrated functions being able to perform speech recognition and synthesis.

For further application to the real life, the system should extract the desired signal when voices of several people are mixed. Also, it should eliminate the noises even though large ones are mixed.

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FAST MARKOV LOCALIZATION IN INDOOR ENVIRONMENT USING SFM ANGLE-HISTOGRAM

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Abstract: Localization is one of the most important issues for mobile robots since all tasks are commanded to a mobile robot based on the assumption that the mobile robot knows its position. Even though non-probabilistic techniques are faster than probabilistic approaches, those are sensitive to measurement errors and a mobile robot may lose its position in complex environments. And most simple features need additional information to represent the characteristics of environments. On the contrary, probabilistic approaches have many advantages since those can cope with sensor noises and can globally localize a mobile robot. However, those probabilistic approaches are time-consuming techniques because of the heavy computational loads due to huge comparative data. In this paper, we propose a fast probabilistic localization method including global localization by remodeling raw laser sensory data using angle histogram to reduce computational loads for localization. The algorithm is experimented successfully by using a mobile robot named KARA.

Keywords- global localization, fast probabilistic localization, sensor remodeling, angle-histgram

1. Introduction

Not only industrial robots are widely used, but also a number of service robots, such as vacuum cleaning robots have been introduced to commercial market. Since many tasks of mobile robots are commanded based on the assumption that each mobile robot knows its position exactly [1], localization that determines the real position of a mobile robot with respect to a world coordinate frame using sensory information and a world model for environments becomes a hot issue in the robot technology.

There are so many sources for mobile robot localizations in indoor environments. Localization algorithm can be classified into two categories according to its methodologies, non-probabilistic approaches and probabilistic approaches. For non-probabilistic approaches, a mobile robot finds its position by feature-matching methods between model features from a reference map for environments and those from real sensory data. Vertices and lines are widely used as matching features. Vertices are the simplest features for the environments, however, it is difficult to discriminate matched vertex among other vertices because a vertex have little information except for its position. Therefore, we must have additional information that represents the environments. In [2], they use 'visibility sectors' made of order of vertices as additional information. An overall map is divided into visibility sectors using vertices of environments. After obtaining vertex data from laser range data, the position of a mobile robot is found by matching them with each visibility sectors. Unfortunately, it cannot discriminate two sectors that have the same order of vertices. In [3], they find all distances between all vertices in an overall reference map to make the reference table during pre-processing. Then, vertices are extracted by using an angle-function from real laser data and a set of distances between all obtained vertices are calculated. Finally, they find the most probable vertex set by matching the length sets in the reference table with the obtained length sets, and determine the position of a mobile. Lines are also used as matching features, however, obtaining method of reliable line information such as Generalized Hough Transform takes much time. Summing up, simple matching features need additional information for representing the characteristics of environments in most case. Therefore, it is good to find a simple feature that needs no additional information. Also, these non-probabilistic approaches are sensitive to measurement errors, and dynamic obstacles and/or frequent changes of environments make the non-probabilistic approaches more erroneous. So, a mobile robot may lose its position when we use non-probabilistic approach.

For probabilistic approaches, a mobile robot finds its position by estimating its probable position from raw sensory data up to current time. Fox[4] proposes Markov localization(ML) method based on a grid map. This method can perform a global localization by updating probabilities of positions where the mobile robot can exist based on the Markov property. However, heavy computational loads for modeling of sensors and actions are required. Dellaert[5] tries to reduce the computational loads by applying Monte Carlo sampling to ML technique. Despite Monte Carlo localization method does not reduce the number of comparative sensor data, sampling of

location candidates reduces the number of comparative positions for probability update. In practice, however, many samples more than expected are required to guarantee a good performance – such as fast convergence - for the proposed approach. Jetto and Longhi[6] used extended Kalman filter(EKF) for mobile robot localization. Using this method, a mobile robot can estimate its heading and position in spite of sensor errors. EKF is faster than ML, however, the EKF algorithm needs initial location of the mobile robot even though some errors are included. Summing up, the probabilistic approaches include heavy computational loads due to large number of comparative sensor data even though two approaches show good localization performance.

In [7], we modify Markov Localization in order to reduce overall computational loads by remodeling raw laser sensory data using *angle-histogram* [8]. The angle-histogram is statistical information of vector differences between two neighbor range data captured by a laser range sensor. The main advantage of using angle-histogram is that we can reduce the number of comparative data, computational loads, and calculation time finally. Another advantage is that we can find the heading angle of the mobile robot within angle resolution in a very fast manner. In [7], we update state probabilities according to the common angle-histogram. This method can reduce the comparative measurement data. However, common angle-histogram is not accurate enough to extract one grid among the area of probable grids. Also, we used no sensor model, but we use the variances between reference and obtained histogram as updating parameters. In this paper, we make the suitable-for-ML angle-histogram and change the updating procedure of ML to make angle-histogram accurate enough to find the real position exactly. Also, we reduce not only the comparative measurement data but also comparative states. Reduction of comparative states makes it faster to localize a robot.

This paper is organized as following: In section 2, we say about ML and our assumptions. In section 3, we explain our sensor remodeling and why we use angle-histogram for this method. Section 4 shows the processes of our localization algorithm. In Section 5, we examine the effectiveness of the proposed algorithm by experimental results. Finally, some conclusions and future works are outlined in Section 6.

2. Problem Definitions

Before starting off our algorithm, we have to define the problems that is solved in this paper and set the assumptions of the environments. For localizing a mobile robot, we use the estimation technique of the robot at current step T. In ML[5], the belief $Bel(L_t)$ has to be conditioned on all previous action a_i and percepts s_i, and we obtain the following equation which describes the belief of being at a location l at time t by applying Bayes' rule.

$$Bel(L_t \mid l) = \frac{P(s_t|L_t=l, s_{1,\cdots,t-1}, a_{1,\cdots,t-1}) P(L_t=l|s_{1,\cdots,t-1}, a_{1,\cdots,t-1})}{P(s_t|s_{1,\cdots,t-1}, a_{1,\cdots,t-1})} \quad (1)$$

Dieter Fox divides this procedure into 3 parts: updating part, prediction part and normalization part. In the prediction part, we predict $P(L_t \mid L_{t-1}, a_{t-1})$ by the belief of being at each previous percept and the mobile robot motion. In the updating part, author applies the assumption of 'independence of perceptions' which means that once we know L_t, all other previous measurements, prior states and actions have no influence on the prediction of S_t. Then, $P(S_t \mid L_t = l, s_{1,\cdots,t-1}, a_{1,\cdots,t-1})$ is converted to $P(S_t \mid L_t)$. In this part, the belief of being at a location l is updated by the probability calculated in the prediction part and current measurements. And we normalize the belief of all percepts in normalization part. Finally, Dieter Fox simplifies the localization equation (1) as

$$Bel(L_t \mid l) = \frac{P(s_t \mid l) P(L_t \mid L_{t-1}, a_{t-1})}{P(s_t \mid L_t)} \quad (2)$$

and this equation is referred as Markov update formula. Figure 1 shows the flowchart of ML.

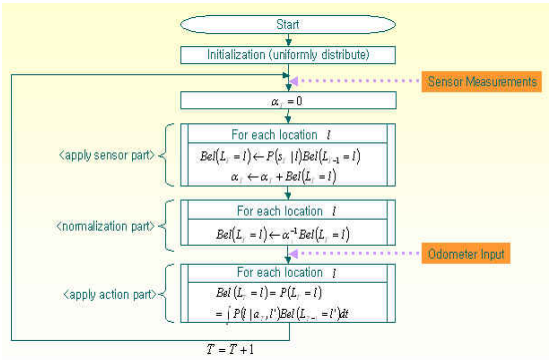


Fig.1. Flowchart of Markov Localization

In this paper, we focused on the updating part of ML. We have to perform $N_{calculation} = N_x \times N_y \times N_\theta \times N_{data}$ at each update step while we use $N_x \times N_y$ grid-map with $\frac{360}{N_\theta}$ angle resolution, and the number of laser data is N_{data}. For example, the size of environments is $30 \times 40(m)$ and we make 300×400 grid-map(cell size of each grid is 10cm) with 2 angle resolution. And the laser range-finder covers frontal half of the robot(the number of laser data is 181), then we have to perform 3,909,600,000 iterations at each step. Heavy calculations make it difficult to perform a task of the robot. Therefore, we reduce the number of calculations $N_{calculation}$ by sensor remodeling.

2.1 Environmental Assumptions

In this paper, our target is a service robot in indoor

environment, and most of us work in an office and stay in an apartment. That is, a service robot works in a building. In a building, rooms and corridors are located as shown in Figure 2. That means, rooms and corridors are located along the walls, and we locate obstacles like table or cabinet parallel to walls for efficiency of area. Also, obtained laser data are point data and we regard the areas of neighbor sets of detected points as obstacles. Therefore, we can regard the environments detected by the laser rangefinder as lines. In this paper, we assume the environmental assumption as (1) large parts of the obstacles are located parallel to walls, (2) all environments are transformed into sets of lines.

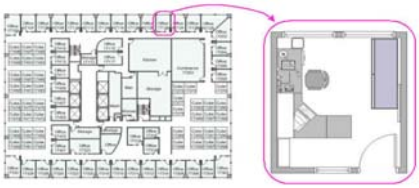
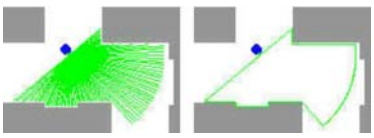


Fig.2. Example of Drawing of an Office Building

3. Sensor Modeling

In the probabilistic approaches including ML, we have to perform a number of iterations to estimate the probabilities of comparative locations according to comparative measurement data per each step. Since the reduction of comparative poses of a robot makes the position estimation unreliable, we can hardly reduce the number of comparative locations even though we want to reduce the computational loads. So, we propose a new approach to reduce the number of comparative measurement data if we want to reduce the computational loads without the loss of reliability.



(a) (b)

Fig.3. Representations of Laser Data

Figure 3-(a) represents laser range data along scan angle of a laser range finder and Figure 3-(b) shows the connection of detected vertex points following the detecting sequence. These two different representations use the same laser data. They have the same information about environments within detectable range but the numbers of data of the two are different. The number of data in Figure 3-(a) is same as the number of laser data, while the information in Figure 3-(b) can be described by some feature points and/or contour information whose number of data is much less than the number of raw laser range data. Therefore, if we are able to extract effective features to describe the raw laser data, the number of data can be decreased. For example, we can extract 7 lines from Figure 3-(b). It is, however, not easy and robust to extract line data since the number of lines can be varied according to the location of the laser range finder for measurement and sometimes we cannot detect short lines due to sensor noise. Furthermore, the process for line extraction from laser data includes much computational loads to use a robust algorithm such as Generalized Hough Transform. So, we adopt angle-histogram as an effective feature to describe the laser range data.

3.1 Angle-Histogram

In [8], angle-histogram is introduced. When we interpret each laser range as a vector, the difference between consecutive vectors can be calculated. The frequency of the occurrence of each vector difference with respect to each angle of vector difference is called angle-histogram. To find an effective angle-histogram for a set of range data, we do not use laser data whose range is maximum because these laser data are represented as an arc in x-y plane and angle difference in the arc region has little influence on overall angle-histogram. Figure 4 shows an example of angle-histogram for laser data in Figure 3. If there is no error in laser data, we can obtain an ideal angle histogram shown in Figure 4-(a). However, there are sensor noises in real laser data and its angle-histogram from these inaccurate laser data does not have these simple patterns. To solve this problem, we filtered noisy laser data by low-pass-filtering method for obtaining similar pattern to ideal angle-histogram. A filtered angle-histogram obtained from noisy laser data is shown in Figure 4-(b).

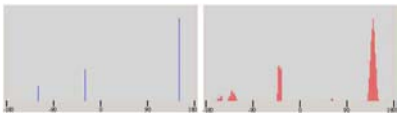


Fig.4. Angle-histogram for Laser Data in Fig. 3 (a) Ideal Angle Histogram, (b) Filtered Real Angle-Histogram

The main advantage of using angle-histogram is that we can reduce computational loads and processing time for localization, and we can find the heading angle of the mobile robot fast because the angle-histogram includes information on the slope and length of detected environments even though laser data has sensor noises as shown in Figure 4-(b). Of course, angle-histogram has disadvantages considering that there can be same angle-histograms even when obtained laser data are quite different because this method simplifies laser range data. However, we can overcome this problem by Suitable-for-ML(SFML) angle-histogram.

4. Localization Using Angle-Histogram

4.1 Basic Concept of ML using Angle-Histogram

The update part of ML is updating the probability of each state using sensor model by laser range data and desired range data of each state. On the other hand, we update the probability of each state using our

sensor model by the length differences between reference and obtained histogram. Figure 5 shows the comparison of our method with ML.

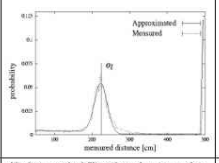
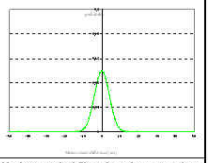
	ML	AH
Kinds of measurement	Scanned laser range data	Angle and length of angle-histogram
Number of measurement data	Number of laser data	4
Sensor model		
Update strategy	Update probability of each pose using sensor model by desired range and laser measurement	Update probability of each pose using sensor model by difference between reference lengths and angle

Fig.5. Comparison Our Method with Markov Localization

The update part follows the following steps. At each time step T, we obtain laser data and calculate modified angle-histogram. For each state L_T, we compare lengths of local maximum points in reference with lengths of corresponding angle in obtained histogram. Using this method, we can reduce the quality of calculation to 4/(number of laser data). Of course, this method has disadvantages: inaccurate length of a obtained histogram, and many similar data in references. And, we cannot reduce comparative states. We only reduce comparative measurement data.

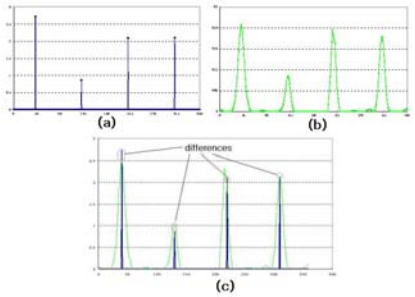


Fig.6. (a) Reference Angle-Histogram, (b) Obtained Angle-Histogram, (c) Length Differences Used in the Update Part

4.2 Probability update based on the SFM Angle-Histogram

1) Obtaining method of exact length of histogram

If we look over a line made from laser data, we can see that it is composed of many lines because of sensor noises as shown in Fig.7. This phenomenon makes the length of angle-histogram inaccurate. In the basic angle-histogram, we obtain the length of histogram just by summing length of vectors that have same angle. However, this length can vary according to noises. Therefore we have to obtain the exact length of histogram. Let the line equation of Fig.7 to be $y = ax + b$. Angle difference between line of l_i and line $y = ax + b$ is $\theta_i - \tan^{-1}(a)$. Therefore, we can obtain the exact length of histogram by

$$\text{real length of histogram} = \sum_{i=1}^{n} \left[l_i \times \cos\left(\theta_i - \tan^{-1}(a)\right) \right]$$

where n is the number of lines.

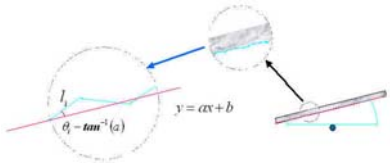


Fig.7. Obtaining Method of Exact Length in Histogram

2) Discriminating method among similar patterns

As we mentioned in section 3, there can be many similar patterns in reference because we simplify many laser data into angle-histogram. To distinguish correct state from a lot of similar patterns, we use an additional reference. We use one minimum range at each state regardless of detecting angle of this range.

3) Reduction of comparative state

We reduce comparative measurement data by angle-histogram. However, if we also can reduce comparative states, calculations are drastically reduced. We reduce comparative states (especially comparative angle) by the characteristics of angle-histogram under the assumption that large parts of the obstacles are located parallel to walls. In the corridor of most buildings, walls are placed in orthogonal. In such orthogonal environments, the angle-histogram becomes more powerful than in common environments due to the special characteristics of angle-histogram. Figure 8-(a) is an example of orthogonal environments, and Figure 8-(b) is angle-histogram of them. In this angle-histogram, we can divide it into 4 parts according to the 0-to-90 degree range area. Part (1) of Figure 8-(b) means the detected length and angle of environment (1) of Figure 8-(a). And environments of Figure 8-(a) are placed in orthogonal. Therefore, we can write each angle and length of Figure 8-(b) as

$$\begin{aligned}
&< \theta_1, l_1 > \\
&< \theta_2, l_2 > =< \theta_2, l_2 > =< \theta_1 + 1 \times 90, l_2 > \\
&< \theta_3, l_3 > =< \theta_3, l_3 > =< \theta_2 + 1 \times 90, l_3 > =< \theta_1 + 2 \times 90, l_3 > \\
&< \theta_4, l_4 > =< \theta_4, l_4 > =< \theta_3 + 1 \times 90, l_4 > =< \theta_1 + 3 \times 90, l_4 >
\end{aligned}$$

In those equations, we can regard each angle as

$$\theta_i = \left[90 \times (i-1) \right] + \theta_1, \quad \text{where } i = 2,3,4$$

Then, if we sum each part of Figure 8-(b) regardless of added 90 degrees(shown in Figure 8-(c)), then we can obtain a pattern of Figure 8-(d). In Figure 8-(d), we can obtain maximum angle θ_a and error boundary ε. This means that the range of heading angle of the robot is

$$(\theta_a - \varepsilon) + (90 \times i) \le heading \le (\theta_a + \varepsilon) + (90 \times i)$$

where $i = 0,1,2,3$. We can use this equation under our environmental assumption. Also, we obtained similar results when we use 1° angle resolution or 4° angle resolution. Therefore, we can also enlarge the angle resolution to 4°.

When we use the length of four local maximum points in the SFML angle-histogram and one minimal range, $N_{calculation}$ becomes

$$N_{calculation} = N_{x'} \times N_{y'} \times N_{\theta'} \times N_{data'}$$
$$= N_x \times N_y \times \left[4 \times \left(N_\theta \times \frac{2\varepsilon}{360}\right)\right] \times \left(N_h + N_m\right)$$
$$= N_x \times N_y \times 10 \times \varepsilon$$

where
- ε : range of possible heading area
- N_h : number of peaks in histogram($=4$)
- N_m : number of minimum range($=1$)
- N_θ : number of comparative angles $\left(= \frac{360}{\text{angle resolution}(=4^\circ)} = 90\right)$

If we use 300×400 grid-map with 2° angle resolution and the number of laser data is 181, then we have to perform 3,909,600,000 calculations when we use ML. If error boundary is $\varepsilon = \pm 10$, our algorithm has to perform 12,000,000 calculations. That is, we can reduce calculation as 1/325 in theoretical results.

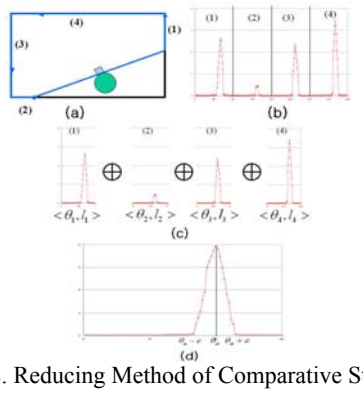


Fig.8. Reducing Method of Comparative States

5. Experimental Results

5.1 Simulation Results

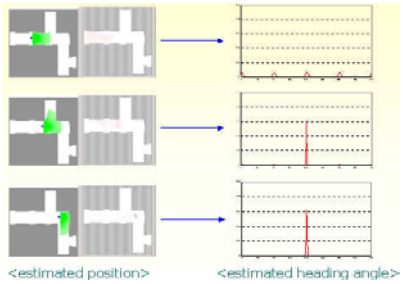


Fig. 9. Simulation Result of Pose Estimation of Basic Angle-Histogram while Robot Moving

We used a personal computer equipped with Pentium-III 700Mhz MPU with 128M RAM. The test-bed for simulation is a mobile robot named KARA developed in our laboratory for experiments. The mobile robot has two differential wheels, and is equipped with a SICK laser range finder that covers frontal half of the robot. Total number of data for each laser scan is 361 when its scan resolution is 0.5 degree and its maximum measurable distance of the laser range finder is set to 4 meters. For simulation, we added white Gaussian noises to laser range data. Environments are set as the corridor including our laboratory.

Figure 9 shows simulation results of basic form of angle-histogram. In this simulation, the physical size of environments is $15 \times 15(m)$ and we make 75×75 (each grid size is 20×20 (cm)) grid-map with 1° angle resolution. The mobile robot moves while obtaining the laser range data. We set the initial probabilities of all state to be uniform distribution before starting these localization steps. Left side of Figure 9 is the probability of estimated position and right side is the probability of estimated heading angle. The probabilities of many states seem to have similar values because there are many similar patterns. Even though the position probabilities are not focused on the position where the mobile robot really exists, we can obtain the heading angle of 0 degree in that step. It is noted that the position error is maintained within an error bound when a mobile robot knows the exact heading angle while x-y position includes some errors. And, if a mobile robot knows the exact x-y position and wrong heading angle, the position error will be increased during the mobile robot is moving. Therefore, our proposed approach will reduce the location error resulted from the error in heading angle of a mobile robot.

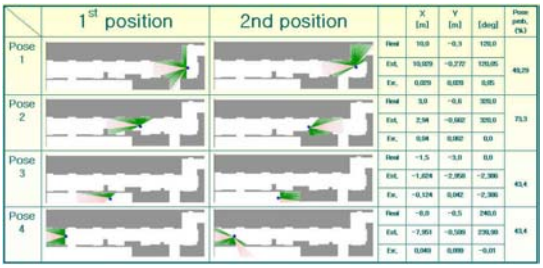


Fig. 10. Simulation Result of Pose Estimation of SFM Angle-Histogram while Robot Rotating

Figure 10 shows simulation results of SFML angle-histogram while robot rotating. In this simulation, the physical size of environments is $25 \times 7(m)$ and we make 250×70 75×75 (each grid size is 10×10 (cm)) grid-map with 4° angle resolution. The average x-error is 6.05cm, y-error is 5.77cm, and heading-error is 0.6 degree. We obtain exact pose when robot rotates. Note that we can obtain less than 1° heading-error even though angle resolution is 4°.

5.2 Experimental Results

Figure 12 shows an experimental result of basic angle-histogram. The robot is moving from the point 'S' to the point 'E' and the localization is executed at circular points in the figure. A dotted circle at each localized point denotes the probable position area. We can see that the area of dotted circle is decreased as performing localization repeatedly. Even though the localization accuracy is decreased as heading angle of robot changes in many localization

algorithms, it is possible to obtain more accurate position when heading angle is changed using our algorithm. Four local maximum points in angle-histogram are used to make a model for environments and to update the probability of each cell. So, the number of iterations for ML in each step is reduced from $125 \times 85 \times 180 \times 181$ to $125 \times 85 \times 180 \times 4$. The position accuracy is less than one grid cell while the rotational error is less than 2 degrees when we use basic angle-histogram.

Fig. 11. Mobile Robot KARA for Experiments

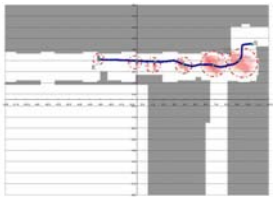


Fig. 12. An Experimental Result of Basic Angle-Histogram

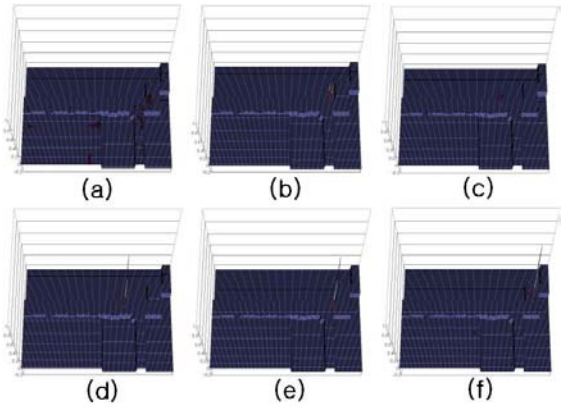


Fig.13. Experimental Results of SFM Angle-Histogram

Figure 13 is an experimental result of SFML angle-histogram. In this experiment, we swept off other obstacles like cabinets and bookshelves to make environments simpler than those of basic angle-histogram. Robot moves from left to right, and turns to return the starting point. We can see that state probabilities of Figure 12 are converged to real position faster than Figure 12 nevertheless of the simplicity of environments. We also can see that the converged state probability becomes nearly 90% after turning. This means that SFML angle-histogram makes better result when robot changes its heading.

6. Conclusions

We have proposed a fast global localization algorithm via sensor data remodeling using angle histogram. Remodeled comparative measurement data using angle histogram for a set of range data is used instead of real range data. By applying the angle histogram for the measurement modeling in estimation process, we can reduce the number of comparative measurement data and computational loads dramatically. Also, we can obtain the heading angle of the mobile robot exactly in a very fast manner. So, the proposed approach will help to reduce navigation errors resulted from the heading errors of a mobile robot.

Future work is concerned on the complex environments that have many patterns. And, sensor data fusion will be investigated to reduce the iteration for position convergence.

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CITIS AS A COLLABORATIVE VIRTUAL ORGANIZATION FOR CONSTRUCTION PROJECTS

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Abstract: The recent use of information technology (IT) has effectively promoted integration of fragmented information under the distributed construction environment. However, to date, many Internet based system for online project collaboration solutions do not provide standard formats in transmitting contractual documents and project-related information specifically for public projects. This paper provides a concept of virtual organization and then examines a CITIS (Contractor integrated Technical Information Service) system for the public construction projects developed in Korea from the viewpoint of virtual organization concept. The CITIS system suggested here has been applied to local branches of the Korean MOCT (Ministry of Construction and Transportation) and it is current in use. Finally, lesson learned from the field trial is provided to advance the current CITIS toward a fully integrated collaborative virtual organization.

Keywords: CITIS, virtual organization, information technology, fully integrated collaborative system, electronic collaboration, online project collaboration solutions

1. INTRODUCTION

The construction industry has suffered from its fragmented structure along the phases of the construction life cycle. The fragmented nature of construction results in low levels of coordination and integration between the different parties involved. Keeping subcontractors, contractors, designers, clients, and other parties supplied with continuous and enormous information has been challenging problem to construction industry. To overcome this limitation, integrating exchange standards and information processing tools has applied to many collaborative application based on information technology (IT). In an attempt to adopt IT into the construction industry, many Project Management Information System(PMIS) and Web based PMIS provide project collaboration solutions spanning all phases of the construction life cycle. However, to date, they do not provide standard formats for documents and information of project, specifically for transactions between public owners and contractors [1]. As a result, a user needs to rekey or reprocess the data once created so as to reuse them in a local system.

This paper provides a concept of virtual organization and then examines an CITIS (Contractor integrated Technical Information Service)system for the public construction projects developed in Korea from the viewpoint of virtual organization concept. The CITIS system is tested in the public road sites to verify its efficiency. Finally, lesson learned from the field trial is provided to advance the current CITIS toward a fully integrated collaborative virtual organization.

2. VIRTUAL ORGANIZATION AND CITIS

2.1 Literature Review of Virtual Organizations

Today's challenging business environment leads to increasing demand for more flexibility and faster reactivity within enterprises. Toward this end, utilization of resources must be optimized at a highest level so that the geographic and temporal production demands of the market are satisfied. However, it can be inefficient that these different functional groups have to work at the same place and at the same time in order to communicate and collaborate. To overcome these barriers, manufacturing industry proposed virtuality concept, as a virtual corporation, virtual factory, virtual enterprise etc. VO (Virtual Organization) concept

started from the concept of virtual corporation since in 1993[2]. Also, Upton and McAfee (1996) defined as "Virtual Factory is a community of dozens, if not hundred, of factories, each focused on what it does best, all linked by an electronic network that would enable them to operate as one flexible and inexpensively - regardless of their locations"[3].
Today there are several definitions depending on the goals of virtual organizations and the scope of resources combined in a virtual networks. Within the field of these domains, specific researches regarding virtual organization/corporation, virtual company, virtual enterprise and virtual factory can be identified (Markfort et. al. 1999). Despite the differences among them, these concepts have similarity in the sense that they concentrate on the joint collaboration through the network, which makes it easy for companies with dissimilar systems to exchange information electronically.[4] This paper adopts a concept of VO that include the whole similarity of related definitions in order for various information from many different organizations are coordinated and come together based on standardized format and work processes to produce the particular output through a network.

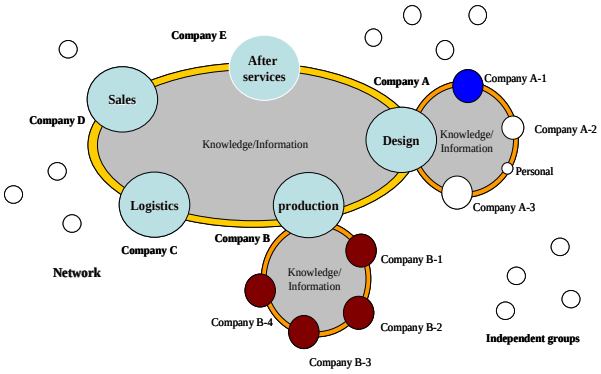

Figure 1. The Organizational Concept of VO in manufacturing industry

(Sources: revised from GNOSIS in Esprit Project)

The primary concept of VO includes the following roles: (1) broker who is selling the services that include marketing activities and information management to the customers; (2) open standards based on the protocols established for the internet which allows members of a community to share information regardless of differences in their individual computer system; (3) a networked manufacturing community that is open and friendly to even the common users; (4) abundant bandwidth that enables the highest-speed links; and (5) security such as firewalls, unbreakable data-encoding scheme, and electronic signature system[3][4][5]. According to Wendy (1999), the basic characters associated with VO concept are summarized as: (1) boundary crossing, (2) complementary core competencies/the pooling of resources, (3) knowledge sharing, (4) geographical dispersion, (5) changing participants, (6) participants equality, and (7) electronic real-time communication[6]. To address these basic characters, Ronald(1999) suggested that VO function should contain the primary services as indicated in Table 1[7].

Table 1. Primary Functions of VO

Function Types	Required Services
Basic Services	Data Service Communication Service Information Technology Service Electronic Certification and Security Service
Business Services	Collaboration Service Knowledge Management Service Coordination Service Process Service Information Service Transaction Service

2.2 CITIS (Contractor Integrated Technical Information Service)

CITIS is a standard used by contractors to deliver contractually specified technical data using a contractor-integrated data management system, instead of having to deliver the information in a printed format. In accordance with a contract, the contractor electronically provides contractual information to the owner through a mutual database server (CITIS server), and the owner then accesses the information in the CITIS server through electronic network, as shown in Figure 1[8].

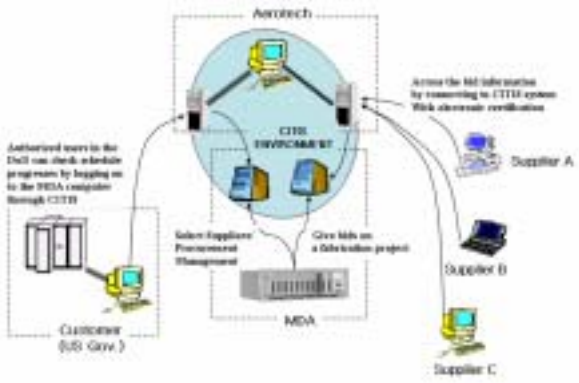

Figure 2. Framework of CITIS gateway in U.S DoD (Source : Andrew McAfee, 1997)

The concept of CITIS has been widely applied for the manufacturing industry as an agile collaborative tool. Especially, McDonnell Douglas Aerospace (MDA) and AeroTech Service Group (ASG) developed commercial CITIS in 1993. This CITIS system facilitated electronic information sharing and

transferring among the companies and their external suppliers, customers, and other partners. Currently, AeroTech Service holds 201 projects, 2,000 suppliers locations, and 234 Web applications and Web sites for CITIS gateway.

2.3 CITIS in Construction

The CITIS concept is a relatively recent introduction in the construction industry. Providentially, several Asian countries such as Japan, Taiwan, and South Korea are extending CITIS concept at the national level toward construction industry. South Korea started from 1998 by MOCT(Minister of Construction and Transportation) on public road construction project. At this present, six local branches of MOCT is applying the CITIS system. The Japanese Ministry of Construction launched their Construction CITIS program in 1996. Japan has been implementing national level IT strategies in construction. As an early exhibition program on CITIS, Japan has conducted various types of field test since 1997 to illustrate how the CITIS concept can be utilized to improve the paper-based construction environment. In the case of Taiwan, starting from 1997, the Ministry of Economy (MOE) introduced the CITIS concept at a national wide level, as an attempt to atomizing construction life-cycle process[9]. The prototype of CITIS system was proposed based on the object oriented techniques so that users can share project information with other applications along the construction life-cycle. Taiwan government presents the conceptual CITIS model and subsequently performs the research to develop the integrated information core model to promote the information sharing with other applicant within the construction industry [9]. In similar case, The OSMOS (Open System for inter-enterprise information Management in dynamic virtual envirOnmentS) is a European project performed by the consortium, which consists of France's CSTB (Centre Scientifique et Technique du Batiment), Information System Institute of University of Salford, and VTT (Technical Research Center of Finland). It aims at providing an infrastructure that underpins the concept of virtual enterprise by promoting co-operation between actors and companies in the construction projects [10].

2.4 Basic Architecture of CITIS system as a construction VO model

On the basis of VO and U.S. DOD CITIS concepts and functions, This paper presents the advanced construction VO model developed for public project in Korea. Originally, U.S. DoD (1993) defined primary functions in CITIS: the core function that the contractor has to provide, and tailorable functions that may be specified according to the contract between owner and contractor. Basically, it consists of information service, data configuration management, CITIS security, data item index, and data exchange standards. However, U.S. DoD only defines the general functions required for CITIS implementation. Subsequently, application functions must be developed with a consideration of adaptation from project management functions. In this context, we established construction CITIS functions in accordance with the primary functions of VO so as to overcome typical limitations being faced in current CITIS systems. Figure 4 presents basic architecture of construction CITIS, which consists of three primary parts - domain part, business part, basic part.

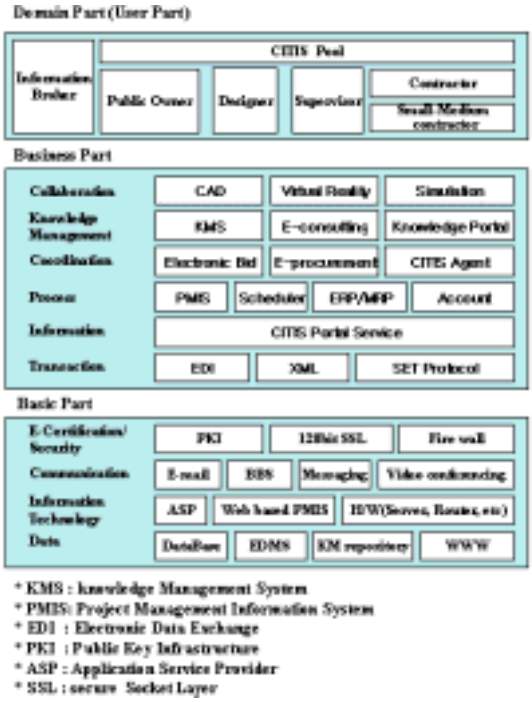

Figure 3. Basic Architecture of Construction VO Model

The domain parts consist of public owners, designers, supervisors and contractors as providers, and a broker as an intermediating function that operates CITIS system. The CITIS structure enables users for boundary crossing, which implies that they are loosely combined in a CITIS pool by dues as an annuity and then rigidly tied to produce the specific products as a project team. In contrast with the domain part, the business part is close to the value adding activity of the participants such as; (1) collaboration service: CAD, real time collaboration and simulation, suppliers chain management; (2) knowledge management service: knowledge provisions for collaboration and project management including know-how and training on setting up a CITIS system and consulting services; (3) coordination service: new application solutions that implement coordination mechanism like procurement actions as well as intermediaries including CITIS agent; (4) process service: whole process or a part of

a process offered by CITIS portal service including internet based project management; (5) information service: specific information required in the process of production including technical specifications, relevant building codes, and construction laws and regulations; and (6) transaction services: a high relevance of compliance to the principle of transaction and timeliness of the services that are back office settlement activity such as EDI, XML, and set protocol. On the other hand, basic service is rather stable and choice of business services should have bases on the basic service; (1) data service: project related data sharable and reusable for the participants characterized by highly standard data and a high stability of the service requirements; (2) communication service: the opinion exchange through the content free communication standards, including the network and required protocols including bulletin, chat rooms or message services for real time communication; (3) information technology service: the hardware and application components like browser and web servers specialized in IT and application hosting; (4) electronic certification and security Service: authorized security standards for authentication, access control, encryption, data integrity, and electronic signatures.

3. THE EVALUATION ON KOREA CONSTRUION CITIS SYSTEM FROM THE VIEWPOINT OF Virtual Organization (VO)

3.1 Korea construction CITIS system Overview

CITIS system of Korea MOCT consists of five sub systems designed for supporting the construction phases such as; (1) owners CITIS server; (2) CITIS agency (broker) server; (3) security and authentication module; (4) CITIS interface with contractor's in-house information system; (5) Electronic Document Management system (EDMS); and (6) Integrated Data Base.

Figure 4. Structure of Construction CITIS

Based on this system, the contractors can transmit the project-related information to the broker CITIS server through the Internet. Subsequently, it is forwarded to the owners CITIS server with the support of socket and SMTP (simple mail transfer protocol) technology. Afterward, the owners make an appropriate decision on the project and then return the document on their decisions to the broker server. Finally, the contractor can retrieve the returned document from the broker server. Particularly, XML formats based on DTD (Data Type Definition) are used in an attempt to communicate electronically among the participants in different computer systems. Figure 5 expressed the role of construction CITIS agent and correlation of participants.

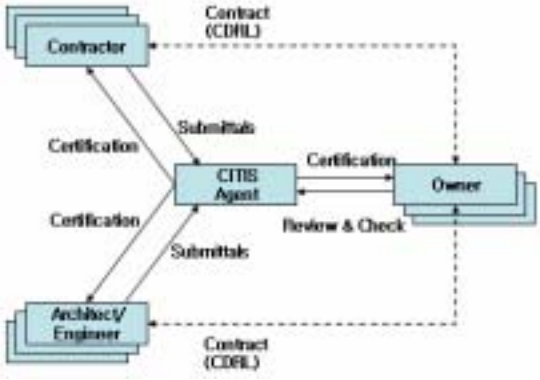

Figure 5. The role of construction CITIS agent

A real system based on the concept of CITIS is shown in Figure 6. The user (owners, designers, inspectors, and contractors) can log into the CITIS server by keying user ID and password and then through approval process, identify connected project name, log time, etc. and execute each accessible menu.

Figure 6. Window for Construction CITIS Menu

The CITIS consists of the following five components: (1) Project Progress Information Management where Project status information can be searched or queried by a project ID and a contractor uploads contractual document for the application of the progress payment by utilizing the project progress management function; (2) Public Notice Management where users can search, modify, and delete public notices regarding the management of

projects; (3) General Information Management that allows the management of general project information such as contract status, user information, submitted information, document registration list and document contents, etc.; (4) Technical Information Management that deals with drawing, specification, construction methods, etc.; and (5) System Management that allows a system manager to control the total system, including code management, bulletin board management, data room management, plug-in management and logging management, and backup of documents and information on projects.

3.2 The result of field test about Korea construction CITIS system

Construction CITIS system is operated for trial application 77 road construction sites from 2003 to 2004. During latest 7 moths, total 2744 contract documents of road projects had used in construction CITIS system. And the result of Multi-users Test(200 user, 100 times) to the CITIS server, CITIS system is not founded error, as performance deterioration and system down, etc.

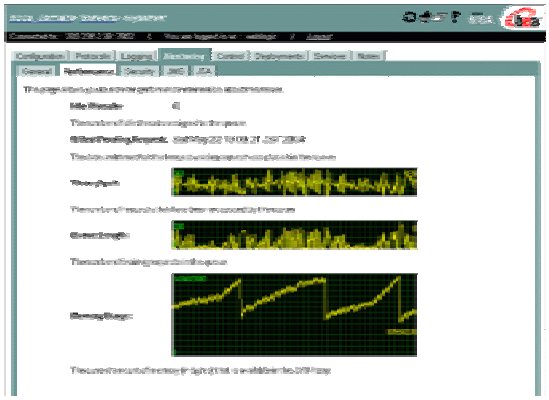

Figure 7. Performance Monitering graph of CITIS web application server (source : CITIS agent interim report)

Table 2 indicates the test results. Subsequently, the CITIS system proved its capacity to transfer the different sizes of documents steadily, showing 14 seconds to 36.5 minutes depending on the size of attached files.

Table 2. Results of Preliminary Multi-user Test

Types of documents	Size of attached files	Processing time
Text	779 Kilo Bytes	14 seconds
	5.16 Mega Bytes	1 min. 5 sec.
	10.6 Mega Bytes	1 min. 48 sec.
	3.24 Mega Bytes	3 min. 22 sec.
Graphics and drawings	50 Mega Bytes	14 min. 15 sec.
	120 Mega Bytes	36 min. 30 sec.

The expected benefits of the system are to reduce not only the current offline delivery time of the construction information but also to minimize the efforts for re-keying and re-processing of the data. The CITIS system handled data and documents electronically which were exchanged between the regional offices, CITIS broker agency, and the contractors on a real-time basis during the project period. Within the context of measuring the benefits, the data coverage was confined to the change order and periodic payment work flow because these works are typically and frequently performed on the construction sites and so considered representative in comparing the cost, speed and data service between as-is and to-be work flow. In a straightforward manner, the application of the system was evaluated to bring the reduction of the time and cost, 35% and 26%, respectively, in the progress payment activity, and 40% and 30% for the design change activity.

3.3 The evaluation on the Korea construction CITIS system from the viewpoint of VO

In spite of good result for field test about Korea construction CITIS system, we considered that the system has characters and functions of VO. Table 3 is results of review for CITIS system from the architectural view of construction VO model

Table 3. Architecture of construction VO model

Characters and Functions of VO		Korea CITIS system
Character	Boundary Crossing	X
	Complementary core competencies / the pooling of resources	X
	Knowledge Sharing	O
	Geographical dispersion	O
	Changing participants	O
	Participants equality	X
	Electronic real time conferencing	X
Function	Collaboration Service	X
	Knowledge Management Service	Δ
	Coordination Service	X
	Process Service	X
	Transaction Service	O
	Information Service	O
	Data Service	O
	Communication Service	X
	Information Technology Service	X
	Electronic Certification and Security Service	O

However, the field management function for contractor and supervisor which the current CITIS system is lacking in, should be established for collaboration to be conducted in the VO as the project is processed in the field. That is, information sharing and monitoring structure is not reflected on it because the contract management functions by ordering public owners has been approached from the exchanging of official contract documents. Therefore, the present CITIS system is concentrated on electronic forward of contract documents, data transmission, and reliability of transmission data.

The CITIS system for mid- and small-companies included in construction CITIS is not equipped with the supply chain management, materials, equipments and managerial functions for field process because of its concentration on providing information with ordering party, These problems have been pointed out through the actual proofs by owners, contracts, supervisors, and it means that construction CITIS should be equipped with the structure and functionalities of virtual company to be established.

4. LESSONS LEARNED AND CONCLUSION

In this research, the authors have put efforts on taking a different view of CITIS (Contractor Integrated Technical Information Service) model in terms of Virtual Organization (VO). As a result, it has been found that CITIS has a limited function on providing collaborative work space. It is more like a electronic document management system only. Often it causes more document work rather than reduces paper-works because many project owners and contractors prefer old-fashioned paper-works to electronic documents. Furthermore, CITIS was not a complete computerized document management system, either. It provided only a fracture of the document management system. In this research, this was proven by applying the CITIS model to 77 construction project for 7 months across the nation.

While CITIS is focused more on the contractual document transmissions, Virtual Organization is a total management of the construction project over virtual (cyber) space. Virtual Organization provides a collaborative work space in which project participants get together and exchange data and information. Given that the construction project is a temporary organization of the project participants (general contractor, A/E, subcontractor etc.), it can expand larger to include extended participants such as project owner and users. Since the information flow is much faster in virtual space, important decision can be made more quickly and efficiently based on more suggestions and ideas of all the participants.

Future research will include the verification of the selected functions of VO by applying them to a real construction projects as many as 300 or more and by survey interviews of the participants.

Acknowledgments

The writers thank all colleagues who have offered constructive criticism of this work as it progressed.

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INTEGRATED PROCESS MANAGEMENT SYSTEM FOR PART-MANUFACTURING AND BUILDING CONSTRUCTION

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Abstract: This paper describes an implementation of the Integrated Construction Process Management System, which includes manufacturing process management features for building parts, and also includes construction process management features at construction site. To observe the flow of the building parts, RFID's are stuck to all of the parts to be managed, and several checkpoints, which we named "gates", are introduced within the coherent process through part-manufacturing and building construction. By means of this, building parts can be tracked certainly, and anyone can know the status and the location of building parts at that instant.

Keywords: integrated process management system, part-manufacturing process management, building construction process management, intensive data management system

1 INTRODUCTION

This paper describes an implementation of the integrated construction process management system, which includes manufacturing process management features for building materials, and also construction process management features at construction site.

Recently, RFID's are getting popular in logistics industries and manufacturing industries. The process management system for building construction and building materials manufacturing must cover these two aspects, and the use of RFID's in construction industries will make the trace-ablity of the building materials more accurate.

When the implementation described here is realized, in a case of some troubles found in building materials, other building materials are re-allocated for the order, and if requested in advance, other new orders are submitted to the materials manufacturers. Those system enables efficient project management, by means of providing all information of the both material manufacturing and building construction processes to all of material designing, material manufacturing, building designing, and building construction sites.

2 APPROACH

In this implementation, we aimed to confirm that the system operates properly on the whole. In order to make its information processing simple, the process management engine uses only typical durations to process each step in the manufacturing materials or installing them, and the bills of materials.

In order to trace WIP(Work In Process)'s, we installed several checkpoints, which we named "gates", within the process through material-manufacturing and building-construction. On WIP's passing these gates, RFID's are read and progress reports are collected to the process management system.

As the due time for passing the final inspection process of the installation to the building is deduced from the overall schedule of the building construction, the due time for passing each gates can be calculated from the given final due time and the typical durations from one gate to the next. In the other hand, when WIP's pass each gates, the estimated time for passing following gates can be calculated from the actual achievement time and the typical durations.

In these way, for each building materials types, we can obtain both due time for all demands passing all gates, and actual or estimated time for all

WIP's. By associating each demands and each WIP's in the order of time passing a predefined gate for each building materials type, we carry out the allocation of demands and WIP's.

In the case of due time of allocated demands is earlier than estimated time of associated WIP passing by, we assume that tardiness is expected and some action is required, at the moment.

The due time for demands are re-calculated every time when the due for final inspection changes, and the estimated time of WIP passing by are re-calculated every time when the WIP passes new gate. The reallocation of the demands and WIP's takes place, when either the list of demands or the list of WIP's sorted in order of time change.

3 THE IMPLEMENTATION

3.1 Gates

In order to trace WIP's, we have set up nine gates within both material-manufacturing and building-construction processes, as follows.

1. Design approved,
2. Ordering raw material,
3. Start processing,
4. Assembling,
5. Shipping out from the manufacturing plant,
6. Carrying into the construction site,
7. Distributing within the construction site,
8. Installing building material in the building,
9. Final inspection.

It is easy for the system to change the total number of gates, to change typical durations from gate to the next. It is also possible to differ the typical durations for calculating due time with the due for the final inspection gate from the durations for calculating estimated time to pass gates with action achievements information.

When the WIP's pass gates, following processes are took place.

1. Reading RFID on the WIP,
2. Converting to the WIP identifier,
3. Logging the time passing the gate,
4. Logging the physical position of WIP,
5. Logging the result of the post-process testing (optional).

These data are accumulated within an actual achievement database resides in the shared data space, described later.

3.2 Tracking Works with RFID's

At each gate, the system gathers actual achievement information by means of RFID's. In this implementation, we assumed to use read-only type RFID's with 128 bit length identifiers.

Generally speaking, as each building materials consists of multiple parts which are manufactured independently in the manufacturing line, single building material may contain multiple RFID's in it. On reading RFID's of a building material, some of multiple RFID's may respond and some may not, but the tracking engine should handle these information properly in any case. In some cases, an assembled WIP may be dis-assembled to find much more matching combination.

So, the tracking engine should have following features.

1. Identifying the WIP from partial RFID's information.
2. Keeping RFID identifiers of all parts consisting the WIP.
3. Keeping tree-structured information including assembling order and part structure, for the case of dis-assembling and re-assembling.

Furthermore, it is expected that reading some particular RFID's instead of entering some information manually, such as operator's name, physical location of the work-cell, and others. So, the tracking system can judge whether given identifier represents some WIP or not.

3.3 Allocation

In this implementation, we use simple algorithm described in the Section 2 to allocate demand to corresponding WIP.

The basic data, which are the typical durations from one gate to the next or previous gate and the bills of materials, are given by initializing agent and stored in the shared data space among multiple processing agents, described later. In this implementation, the typical durations for due date deduction may differ from the typical durations for calculating estimated times passing following gates. Both durations are defined for all demand and WIP types as default values, but the users can define other values to override them for respective types.

We named the lists of same type WIP's, which

are arranged in the order of actual expected time passing a predefined gate, as "preceding list." In other hand, we named the list of same type demand, which are arranged in the order of due time at a predefined gate, as "priority list." Their priority is defined only by the due time order, and we ignore any other value-related information which may affect on priority of demands.

All demands and WIP's are processed in building material type by type, and in the case of the material type made from multiple parts, the demands of those parts is newly created according to the bills of materials at the gate at which those parts are assembled together. The due time of the parts is set as same as the due time of the combined WIP at the same gate. The estimated time of one WIP to pass the assembling gate is calculated as the latest one of the estimated time of its parts to pass the gate.

In order of simplify the allocation algorithms, we assumed that there is no part types which are assembled into multiple building materials, in order to omit the idea of priority.

3.4 User Interface

In this subsection, we describe the user interface screens implemented. The user interface of this system was developed as the application of World Wide Web system, in order to make them accessible from not only desk-top computer systems but also portable data terminals.

Figure 1 shows the status display for one particular association of the demand and the WIP, including the parts which demands and WIP's consists of. In each table entry, the upper row contains date information in the format of YYYYMMDD, and the lower one contains time in the format of HHMMSS.

The table entries with while background color show the due time of the demand for that gate, those with green background color show the actual achievement time of the WIP to pass the gate, and those with blue background color show the estimated time of the WIP to pass the gate calculated from the actual achievement time for the last gate passed and typical duration time.

In this table, the demands and the WIP's are shown in the preceding list or the priority list order.

The neighboring entries consisting upper demand line and lower WIP line show the allocation of demand and WIP. This allocation is subject to change, and the indications changes when due dates are changed or WIP passes new gate. In the case of tardiness expected in some allocated pairs, their actual achievement date and time are shown in red characters.

Figure 2 shows the status display for one particular type of building materials, including the parts which demands and WIP's consists of.

This example shows that two building materials

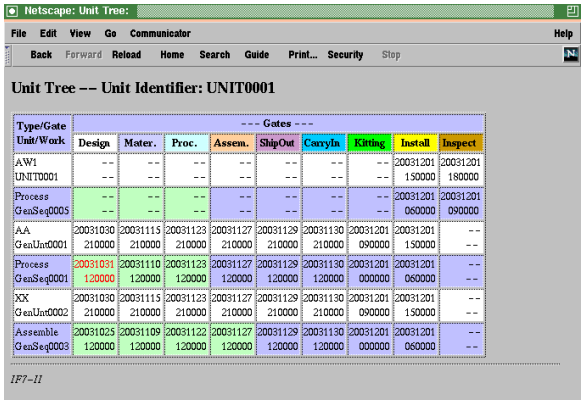

Figure 1: Due time to passing gates and estimated time passing followings

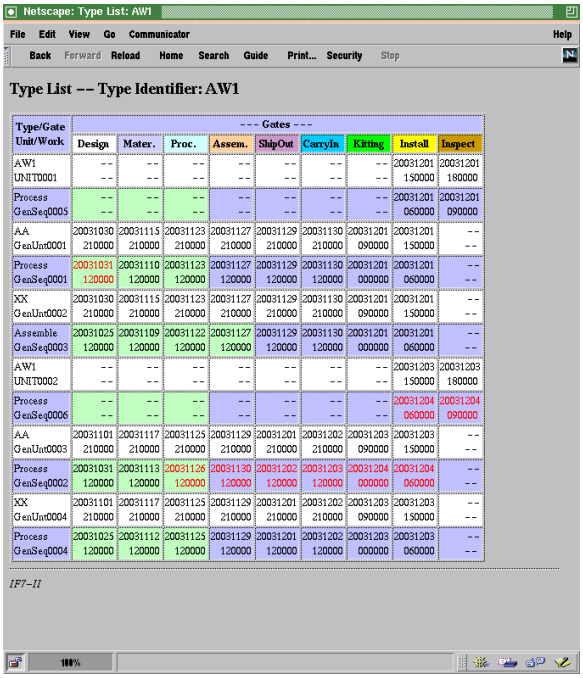

Figure 2: Status display for all works of specified building material type

are currently under processing, and one WIP recovered its tardiness at the first gate, by shorten the duration for processing from the first gate to the second, but another WIP has delayed at the last gate it passed and tardiness at the gate for the final inspection is expected.

In order to recover such situations, one of following behavior is feasible.

1. To shorten the duration from the gate to the next, as the first part has been done.
2. To postpone the due time for the final inspection of the building materials installation.

Figure 3 show the case of postponing the due time of the final inspection of the unit with unit-ID UNIT0001 for four days. As the result, the due time of the unit UNIT0001 and that of the unit UNIT0002 are reversed, and the parts set which are going to be used for those units are exchanged. Figure 4 shows the input form to report that WIP passes a gate.

Operators in the sites have their own PDA (Personal Digital Assistance) or Pocket-PC terminals, and their terminals have antennas to receive signal from RFID's. Reading this identifier signal, the process management system shows reporting forms. What the operators have to do is only tapping (touching with pointing pen) one of two buttons on its panel, PASS or FAIL.

After entering these information, the actual achievement data is updated and estimated times to pass the following gates are calculated, and the re-allocation is took place if required.

Figure 5 shows the input form to report the change of due time for one gate passing.

In this form, the identifier of the demand, the gate of which due time being changed, and the newly given due time are filled in. After entering these information, the due time for former gates are calculated, and re-allocation is done if required.

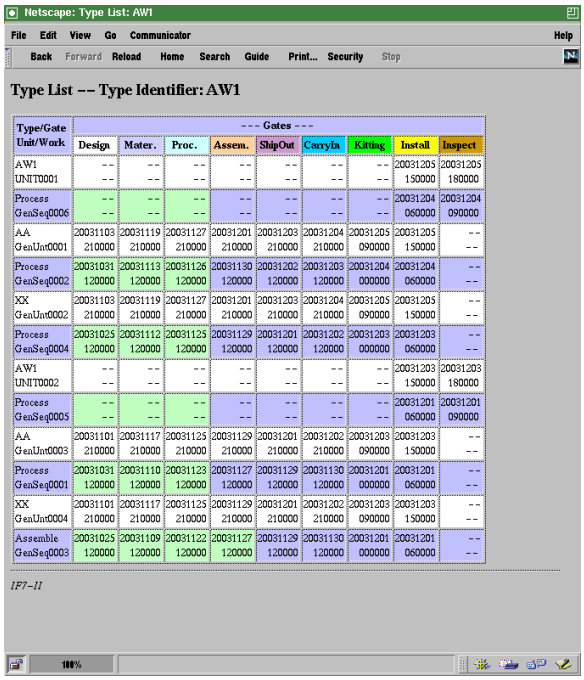

Figure 3: Status after changing due time

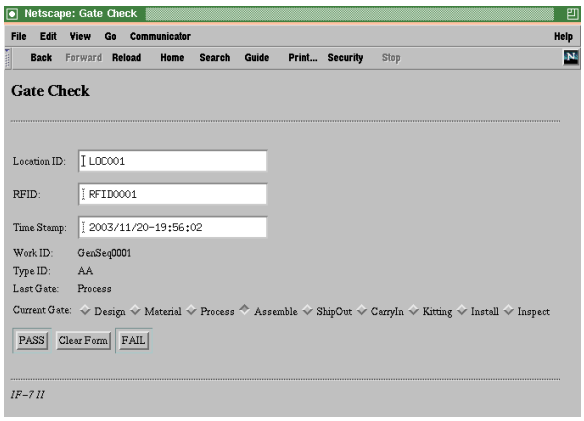

Figure 4: Input form to report gate passing

4 THE INFRASTRUCTURE SYSTEM

In this study, we used the system named "Glue Logic" [1-3] as the infrastructure to support multiple-agent processing system, in order to implement a kernel of MES (Manufacturing Execution System) controlling manufacturing processes.

The Glue Logic, which is developed by the Takata Laboratory of the University of

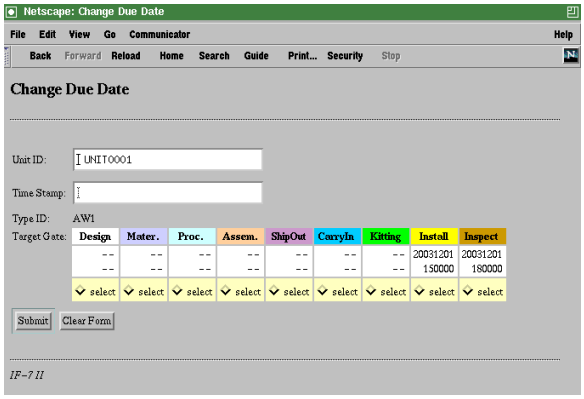

Figure 5: Input form to change due time for a gate passing

Electro-Communications in Japan, includes an implementation of the active database and the network transparent programming environment, and supports data processing in the event driven programming paradigm.

4.1 Active Database

The active database is a subclass of the database systems, of which databases have an abilities to behave when it finds some changes of its contents, without waiting for external actions.

The change of the contents includes;

- when data is changed,
- when some relations are formed,
- when some new data become available.

And the behavior executed on these incidents includes;

- changing contents of the database,
- calculating certain expression and assign the result into some variable,
- sending message to some client agents.

4.2 Aims and Functionalities of the Glue Logic

The Glue Logic is designed to make building manufacturing work-cell control systems easy and flexible, and also coordinates agents by means of followings;

- Providing field of coordination
- Implementing shared data space among agents
- Virtualizing agents within the name space of shared data
- Controlling message passing among agents
- Implementing mutual execution primitives
- Prompting agents to start processing
- Adapting control systems to real-time and network processing environment

As the Glue Logic supports event notification and condition monitoring features based on active database scheme, users can easily build real-time and event-driven application agents, only waiting for notification messages from the Glue Logic.

Each agents in an application system can be developed concurrently, and can be added, deleted or changed freely without modifying other existing agents. As the result of these, the Glue Logic compliant agents are easy to re-use, and the users can build large libraries of application agents.

4.3 Role of the Glue Logic

In this implementation, the flow of its data processing is as follows.

1. When a WIP reaches new gate, or when a due time of a demand changes, the corresponding agent is activated via a Common Gateway Interface (CGI) for the World Wide Web user interface. These agents updates the actual achievement records for WIP's or the due time requirement records for demands. These records are kept in the shared data space in the Glue Logic.
2. When data within the shared data space is changed, some messages are sent from Glue Logic to agents which have already subscribed to the data items. This time, the agents keeping preceding lists or priority lists are informed, and update those contents.
3. When the contents of preceding lists or priority lists are changed, the notification message is sent from Glue Logic to the allocation agent. The allocation agent reads preceding lists and priority lists, and then makeup associations between demands and WIP's.

As described above, the Glue Logic plays role of the conductor or alike of whole system.

5 EVALUATION

5.1 Evaluation on the performance

We implement whole system on Sun Netra T1 processor running on Solaris 8 operating system. Through this implementation, we found following performance considerations.

1. Re-allocation of the demand hardly took place unless due time of final inspection changed or some WIP's pass other preceding WIPS's.
2. In many cases, as there are less than tens of WIP's concurrently being processed in both material-manufacturing and building-construction sites, re-allocation of the demand takes only a few seconds. But in the case of building materials consisting multiple parts, as the re-allocation process occurs in multiple stages, it may takes more than ten seconds.
3. It may takes a few minutes for operators to input data for gate passing process or changing due time for the final inspection, especially in

the case multiple changes have come. So, some features to inhibit processing during data entry may be required to prevent needless data processing.

5.2 Evaluation on the extend-ability

We used multiple agent support system in the implementation, in order to ease future extension of functionality. From this point of view, we found followings.

1. All information on the actual process achievements are kept within a database. This makes any other agents being able to utilize these data for processing and user interface purpose, such as followings;
   - displaying status of building materials within building floor plan chart
   - sending e-mail to notify shortage or tardiness of some materials, within a few seconds.
2. It seems to be appropriate that the conversion from the identifier of RFID to building material identifier should be done by specialized subsystem in the management system. There may be many class of RFID's other than expressing WIP's.

5.3 Evaluation on the limitation

In this implementation, we introduced some limitations to simplify the system. They are as follows.

1. There is no problem solving engine to minimize cost.
   In order to find best solution of re-allocation, it is required to minimize cost to re-distribute building materials, or in some cases it is required to determine which WIP to be scraped. Solving this problem may need massive computational power, because there may be combinational explosion.
   In the other hand, we can not define the function to evaluate the cost itself clearly in the practical world. For example, in many cases, two types of building materials are not equivalent in their priority.
2. There is no clear decision rules to be embedded within the system.
   Some incidents can be processed automatically without human interventions, but some require human approvals. There is no clear border and the best way depends on its environment.
3. In the calculation of the due time and estimated time to pass, we use "typical durations." These values are constants and have less accuracy. In the following research, we have to link with APS (Advanced Planning and Scheduling) systems and MRP (Manufacturing Resource Planning) systems.

6 CONCLUSION

Through this implementation described above, we found that the integrated process management system including both part-manufacturing and building construction is feasible enough.
In coming years, we would like to test next implementation at the actual manufacturing and construction sites.

Acknowledgments

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A DEVELOPMENT OF INTERACTIVE TASK GENERATOR BASED ON TASK LOCATION INFORMATION ANALYSIS

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Abstract: A daily report is one of the critical documents in construction projects, since it helps them keep track of various as-built information such as task performed, manpower, equipment, and material used on a daily basis. Despite the important role in progress management, the daily reporting process is time-consuming, and the representation of task information on daily reports are not effective enough to accumulate daily as-built information for further use in project management. Task information is composed of a specific work type and a location where the task is performed, which means that the same type of work is repeated over the locations. However, in many cases the task locations are described inconsistently depending on a reporter's preference or experience. Without representing task location information in a consistent and accurate manner, it is difficult to accumulate and to reuse as-built information. The objective of this research is to build a framework for generating task information which can be efficiently accumulated and reused for progress management. To do so, this research built a task information model with a focus on the representation of task location associated with a work type, based on the combination of location facets, such as site, building, floor, space, and element. Finally an information system was developed to support automated and interactive generation of task information.

Keywords: Daily Reports, Task, Location, Space, Information Model, Information System, Database

1. INTRODUCTION

A daily report is one of the critical documents in construction projects, since it helps them keep track of various as-built information such as tasks performed, manpower, equipment, and material used on a daily basis. Despite the important role in progress management, the daily reporting process is time-consuming, and the representation of task information on daily reports are not effective enough to accumulate daily as-built information for further use in project management.

Task information is composed of a specific work type and a location where the task is performed, which means that the same type of work is repeated over the locations. However, in many cases the task locations are described differently depending on a reporter's preference or experience. Without representing task location information effectively, it is difficult to accumulate and reuse as-built information. This problem can get even worse in an apartment housing project that has about 10 high-rise buildings of 20 to 25 stories with over 1,000 residential units.

The objective of this research is to build a framework for generating task information which can be efficiently accumulated and reused for progress management in an apartment housing construction project. To do so, this research built a task information model with a focus on the representation of task location associated with a work type, and developed an information system that supports automated and interactive generation of task information.

2. TASKS AND DAILY REPORTS

2.1 Definition of a task

Popescu [1] defined a task and an activity as follows: "A task is a constituent of an activity - a portion of an activity that has duration of less than the total duration of the activity, while an activity is the fundamental unit of work in a project plan and schedule. Each work activity has a defined geographical boundary, a concise description of the work to be performed, and an estimated duration during which the work can be performed. Activities can also have detailed resource and cost estimates."

Based on the definition, a task in this research means that it is a unit for the daily progress management by each contract; it is performed by a single crew at a specific work location; and it is charged with by a specific contractor. In addition, in a sense that tasks represent more detailed unit than activities that are usually managed on a weekly or monthly basis, tasks are sub-activities of an activity.

2.2 Tasks in daily reporting system

Research needs on structuring the task information to resolve the cumbersome and error-prone process of daily reporting, and difficulties in accumulation of as-built information have been raised by a lot of researchers [2, 3, 4]. And others [5, 6] emphasized the importance of management at the task level, which is more detailed than at the activity level, for more accurate information management.

However, it seems that the problems are not quite resolved effectively at this point. Through site visit, exhibitions, and interviews with practitioners and system developers, existing daily reporting systems were surveyed and analyzed. The results show two patterns. First, there is lack of consideration for an information structure to present tasks in a consistent way. In this case, users input tasks performed on that day manually so that even the same type of tasks are presented differently due to an individual's preference for terminology or experience. In particular, work locations are inconsistently presented in the daily reports even by the same person. Secondly, although some systems have an information structure to present work locations, the structure has too little flexibility to present varied work locations. In this reason, locations are not presented effectively particularly for such tasks as finish work, interior work, etc.

3. TASK INFORMATION MODEL

3.1 Analysis of task information on daily reports

The analysis of daily reports used by general contractors in apartment housing projects shows that task information is collected on a daily basis, and is presented in the combination of a work type for the task and a work location where the task occurs. Work types are usually standardized at the company level, but locations are neither standardized nor consistent although they implicitly represent combination of building, floor, space, and element types of information. Table 1 shows how work types can be combined by buildings, spaces, and elements to make up task information in an apartment housing project.
It is found that tasks of the majority of work types can be clearly presented by combination of building and floor information only. However, in several work types, such as finish works and interior works, information on various types of rooms, spaces, and elements often needs to be combined with variety in addition to information on buildings and floors to present tasks as shown in Table 1.

Examples on the combination patterns for tasks in Table 1 can also be varied depending on the characteristics of a project. For example, if the cost of a certain work type takes only a small portion in the total cost, only a few tasks for the work type might be necessary for progress management, and only one or two location items would be combined with the work type to present the tasks. However, in the opposite case, a lot of tasks at more detailed level might have to be made by combining as many location items as possible with the work type. Therefore the information structure for tasks should be flexible enough to present tasks with variety depending on work types and characteristics of a project while keeping consistent and standardized terms of work types, buildings, floors, spaces, elements, etc.

Table 1. Combination of work types and location facets

Work types			Location facets			
High level	Medium level	Low level	Bldg	Spaces		Elements
				Floor	Room or other types	
Reinforced Concrete	Form work	Lift gang forms	●	●		
		Erect forms	●	●		Column Beam Wall, Slab
		Strip forms	●	●		Wall, Slab
	Rebar	Prepare rebars	×	×		
		Erect rebar	●	●		Column Beam Wall, Slab
	casting	Placing conc.	●	●		
Finish	Interior finish	Plaster Coat 1	●	●	Bedroom, Bathroom, Kitchen, Staircase	Wall Ceiling
		Plaster Cost 2	●	●	Bedroom, Bathroom, Kitchen, Staircase	Wall Ceiling
	Exterior finish	Finish Coat 1	●			
		Finish Coat 2	●			
		Grinding	●	●		

3.2 Task information model

Based on the analysis on task information mentioned above, information types and their relationships were identified with a focus on components of task

information that are work types, buildings, spaces, and elements. An information model was developed to assign the combination of location-related facets into work types at the standard level, and it enables to modify the combination of locations so that tasks can be generated depending the characteristics of a given project.

To develop a task information model, the concepts from Uniclass [7] and Industry Foundation Classes (IFC) [8] were adapted. Kang and Paulson [9] insisted that existing classification systems are neither decomposed enough at more detailed level nor inclusive enough to support the presentation of construction projects at more detail level. Furthermore their successive research [10] recommended the utilization of faceted classification system like Uniclass rather than fixed hierarchical systems. Meanwhile, the primary IFC element hierarchy is based on that a project is a top-level container that has one or more sites; a site has one or more buildings; a building has one or more stories (floors); each story has spaces; and spaces are made up of one or more elements [11]. Therefore, this research utilized the facet concept from Uniclass for flexible combination, and the facets were derived from the element hierarchy concept from IFC. That is, project, site, building, floor, space, and element are combined with flexibility based on the characteristics of a work section and a project. As a result, the task information model is proposed as shown in Figure 1.

The task information model was developed by using the class diagram of Unified Modeling Language (UML) [12]. Each box represents a class and a line represents a relationship between two classes. In this model, **Tasks** has relationships with all other classes since instances for the **Task** classes are generated with combining a **Work Item** instance with instances of **Sites**, **Buildings**, **Spaces**, and **Elements** classes, where **Spaces**, in turn, has 4 subclasses. Floor information is not represented in a separate class in this model, since it is embedded as attributes in the **Buildings** class.

The **Spaces** class is specialized into various subclasses as shown in Figure 1, and they are referred to the space facet of Uniclass [7]. Table 2 shows some of instances for the subclasses. Since the subclasses are minimal to verify the concept of the task information model, additional classes as well as instances can be included as necessary.

Table 2 Instances in Spaces and Elements

Subclasses of Spaces				Elements
Vertically Divided Parts of Building	Rooms	Circulation Spaces	External Spaces	
Wing Bay Core	Residential unit Bedroom Bathroom Living room Kitchen Closet	Entrance hall Lobby Elevator shaft Stair case Corridor Balcony	External parking lot Tennis court Courtyards	Footing Floor Stair Roof External wall Internal wall Ceiling Slab

Based on the concept of the facet combination of Uniclass, the primary keys (task codes) of **Tasks** instances are represented with variety as shown in Table 3. Depending on the characteristics of a work type or a project, a work item is combined with all or some of the location facets, such as building, floor, space, and element. For example, the work of excavation is combined with only building information to create the task information of "Bldg101-Excavation" and the task code of "W0401-03:B101." In addition, to present task information more specifically, more than one item can be combined to represent one facet. The example of the finish coat work in Table 3 shows the combination of

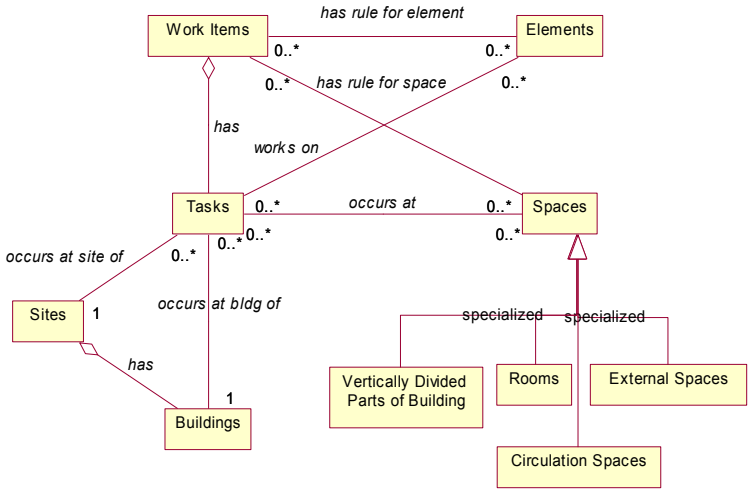

Figure 1. Task Information Model

wall and ceiling in the element facet to create the task named "Bldg 101-Floor1-Bedroom-Wall-Ceiling-Finish coat."

Table 3. Examples of task information and code

W	Location facets						Task Information /Task Code
	B	Floor			S	E	
		FB	FF	FP			
Excava-tion	●	×	×	×	.	.	Bldg101-Excavation / W04-01-03:B101
Erect rebar	●	×	×	×	.	Footing	Bldg101-Footings-Erect rebar / W06-01-02:B101:E15
Erect form	●	●	●	●	.	Slab	Bldg 101-Floor1-Slab-Erect form W06-02-03:B101:FF01
Finish Coat	●	●	●	●	bedroom	Wall & Ceiling	Bldg 101-Floor1-Bedroom-Wall-Ceiling-Finish coat /W12-01-02:B101:FF01:S511:E15:E02
Ceramic tile	●	●	●	●	Bedroom &Kitchen		Bldg 101-Floor1-Bedroom-Kitchen-Ceramic tile / W18-03-01:B101:FF01:S505-S508

W: Work item
B: Building
FB:Basement
FF:1st floor and above
FP:Penthouse
S:Space
E:Element

4. TASK GENERATOR

Based on the task information model described above, an information system, called Interactive Task Generator (ITG), was developed to generate task information that can be managed in daily reporting process. The system enables a user to define rules for each work type at a standard level, and then to modify them depending on the characteristics of a project to create task information at a project level. The details on ITG are described in the followings.

4.1 System architecture

For the development of ITG, Microsoft SQL 2000 was used for database, and C# of Visual Studio .Net was used for system programming. ITG has two modes: the first one is a standard mode where rules for combination of location facets, such as building, floor, space and element, are assigned and managed in each work type at a standard level; and the second one is a project mode where rules can be modified and task information is generated based on the project information, such as the number of buildings, the number of floors in each building, spaces, and elements.

4.2 ITG system

Figure 2 shows generating tasks for the ceramic tile work. A user selects a work item in the "Workitems" tree view, and manages rules by changing selections on "Site/Building," "Spaces," and "Elements" for the selected work item. Since rules have already been assigned at a standard mode, a user can modify the rules assigned by default, with regarding the characteristics of a project. Generated tasks are listed

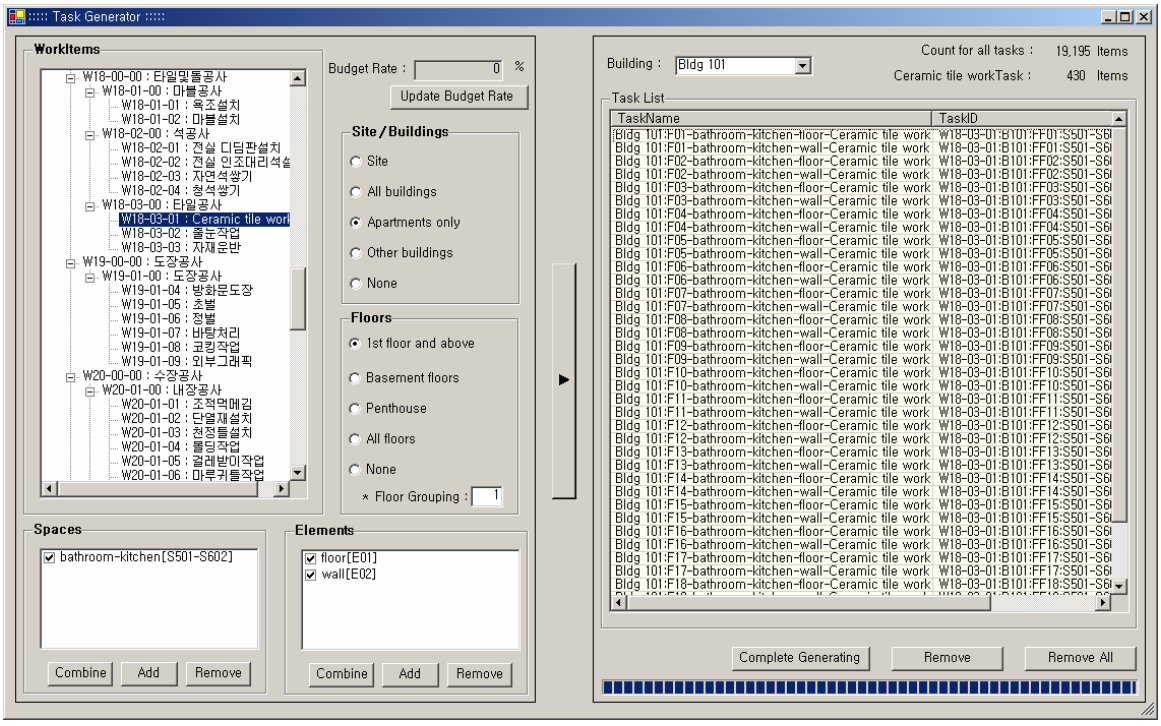

Figure 2. Task Generator

on the right side of the window, and the number of generated tasks for the selected work item and the total number of all tasks are shown at the upper right corner.

Considering the rules, "Site/Buildings" specifies whether a work item is divided at the site or building level, while "Floors" enables to manage tasks by floors in various options: tasks for the 1st and above floors only, for basement floors only, for penthouse only, and for all floors. In addition, "Floor Grouping" enables to create tasks by a group of more than two floors. Meanwhile, "Spaces" and "Elements" provide a way to variously combine items for each as shown in Table 3.

Furthermore, ITG allows a user to gradually create tasks for a work item by changing the rule options. For example, if a basement structure of a building is a beam and slab system while a structure at the upper ground level is a cross wall system, a user can create tasks of basement floors first, and, in turn, he/she can create tasks of 1st floor and above only as shown in Figure 3. Also, a user can delete specific tasks and generate new ones with different rule options. In this manner, ITG provides a user with an interactive way to handle tasks for each work item.

The number of generated tasks as well as the detail level of each task can be varied by the combination of location facets. If tasks are generated at more detailed level, the number of tasks will increase and become a burden to the progress management. However, in the opposite case, tasks will not be used effectively for the management. At this time, the tradeoff between the number of tasks and the detail levels of tasks are dependent on trial and error. Optimizing them through an objective evaluation method could make the progress management even more effective and efficient.

4.3 Validation and verification

ITG was validated through a pilot test at an apartment construction project in Osan, Korea. The construction project has seven of 20-story buildings and three of 25-story buildings with reinforced concrete structures. The test was performed with a focus on whether the rules for tasks are appropriate, and tasks can be generated with meeting the characteristics of the project. Tasks were generated for total 125 work items in the architecture discipline. The first test was performed with setting the rules as detailed as possible without any combination in each facet of space and element, and a total of 38,845 tasks were generated. In the second test, a practitioner modified the rules by combining items in each of space and element facets to make tasks more manageable and applicable at practice. As a result, total 19,195 tasks were generated. This shows that the number of tasks generated for a project can be optimized depending on how space and element items are selected and combined.

Furthermore, considering the schedule of the construction project, the maximum number of tasks for 10 days is 772, and they occur during finish and interior works. Since most of tasks have the duration of only one or two days, about 150 tasks are to be checked by resident engineers. The total number of generated tasks in this project, which is 19,195, might seem to be huge, however, the number of tasks

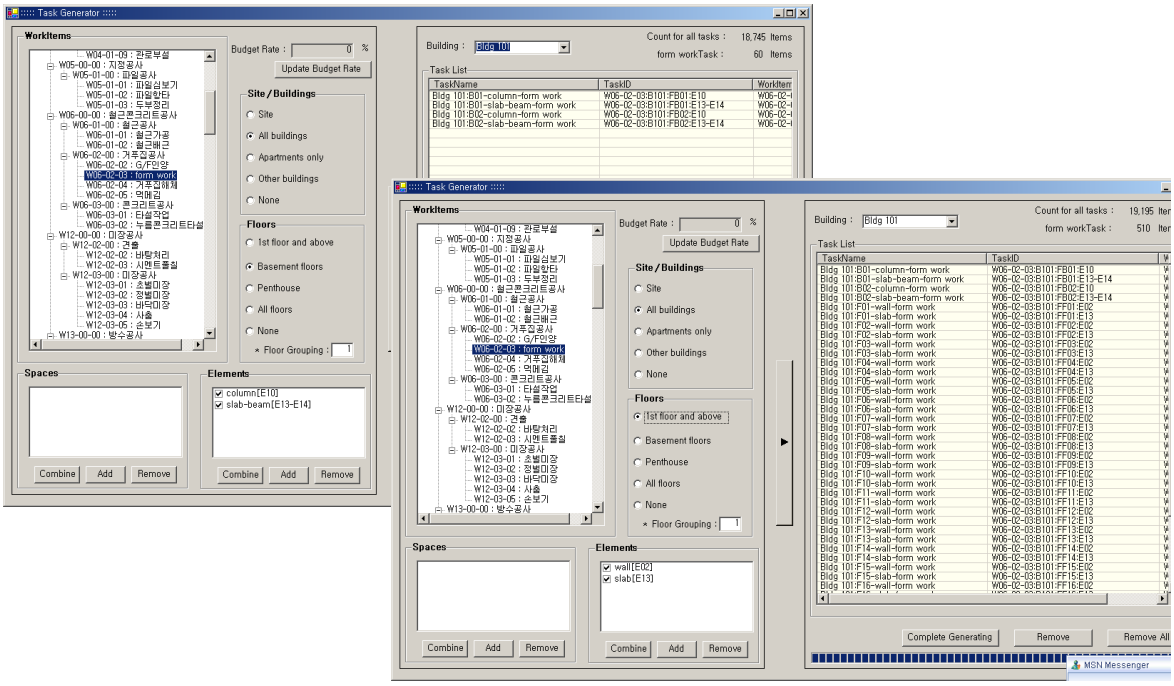

Figure 3. Task Generator

to be checked at a peak day is about 150, and they are divided by the number of resident engineers working on daily checking. In the pilot project, since there were four engineers, they checked about 37-38 tasks per person at the peak time. In addition, tasks with more detailed information could improve the overall daily reporting process since tasks are presented in a more specific and accurate way. This would improve the communication with project participants as well, since more specific and consistent task information is shared and communicated among them.

5. CONCLUSIONS

This research developed an information model and a system to generate task information for more effective and efficient daily reporting. The information model was built on the basis of the combination of a work type with location facets, such as the site, building, floor, space, and element, by adopting the facet-based concept from Uniclass and the element hierarchy from IFC. A task generator called ITG was developed to manage rules for location facets of each work type as well as to generate tasks depending on the characteristics of a given project. The model and the system were successfully tested at a real construction project for validation and verification.

The task information model proposed in this research is being incorporated into a daily reporting system where all tasks are generated at the early stage of a project, and on each day tasks to be performed is selected and checked by engineers as the project goes on. The model could be further utilized for generating activities by controlling the combination of location facets or easily integrated with activities since task are sub-activities.

ACKNOWLEDGEMENTS

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Model Development of the Material Tracking System for High-Rise Building Construction Project Using RFID Technology

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Current study of material management on construction site insists that the ratio of material handling costs to total project costs varies in 30 to 80% depends on the type of construction and the cost of materials [1]. Site layout planning and material management are fundamental to reduce materials handling and re-handling costs and to enhance the efficiency of construction operation for high-rise building. Moreover, these are useful to control planned construction schedule by eliminating the factors related to spatial conflicts due to limited space. There is a need for tracking and controlling effectively material loading and delivery time especially during finishing-work phases to eliminate the need for laydown space on site. Hence, it is essential for monitoring of relevant information regarding material procurement in construction sites and it is the key factor for successful site control and adopting Just-in-Time concept in high-rise building construction. Eventually, the material tracking system is very important for requisition, delivery, and movement of the materials in time. In this paper, the material tracking system using RFID (Radio Frequency IDentification) technique is introduced. Using this system, the materials are going to be efficiently tracked and managed in finishing-work phases.

Keywords : RFID, high-rise building, finishing work phases, procurement, material tracking

1. INTRODUCTION

As on-site stockyard is limited in high-rise building construction underway downtown and transportation of materials in large quantity and movement of lots of crews and equipment need to be made in a confined environment, it is always difficult to allocate space for storing and moving material. As a result, tracking and delivery of material in time for delaying construction process has become critical to efficient management of construction resources. Notably, as finishing-work stage requires resources in largest quantity compared to other construction stages, there is a pending need for arrangement by which delivery of materials may be monitored real time to facilitate construction progress.

The higher the building is, the more critical it is that various materials be delivered and stocked in time as different processes are required to be in progress at the same time. In addition, information generated at various steps of construction workflow with regard to design or construction takes a lot of time to reach sub-contractors working on site and the speed of communication has an absolute impact on construction progress.

To address the issue, a systematic support for material management and control of materials needs to be provided, which calls for a material tracking system designed to ensure just-in-time delivery of required materials in right quantity and to provide constant monitoring capability. This research has attempted to propose a system development model intended to provide efficient tracking capability based on RFID (Radio Frequency IDentification) technology to support material procurement in finishing work stage of high-rise building construction projects.

Scope of this research was limited to proposing a prototype model of material tracking system for ceiling using RFID technology. Following methodology was applied to analyze the characteristics of ceiling material procurement flow and identify processes to which RFID technology could be applied:

- Perform literature surveys and interviews with RFID vendors to find out RFID system components, their technical features and application status
- Examine ceiling material procurement flow by studying literatures and interviewing experts
- Propose an approach to develop prototype model of material tracking system based on RFID technologies and aligned to characteristics of ceiling materials.

2. Literature Survey

2.1 RFID technology

RFID refers to a systematic arrangement where chips are embedded in tags attached to products to store the information created at various steps of material procurement process including purchase order placement, production, procurement, storing and site delivery. Readers equipped with own antenna

read data stored in them and the chips are integrated with information management system through mobile communication network interface.

As illustrated in Figure 1, RFID system comprises of antenna-attached reader, an antenna capable of transmitting/receiving radio frequency, data-storing tag and server exchanging data in accordance with a protocol through communication network.

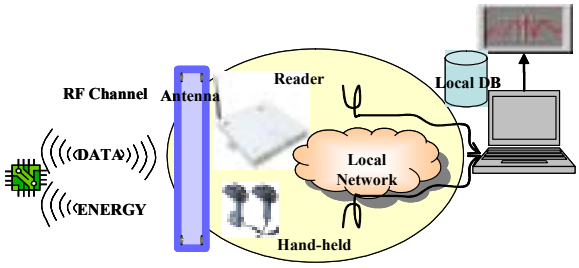

Figure 1. RFID System Configuration

Depending on whether supply of power is required or not, RFID tag is classified into active type that needs its own power supply or passive type that is activated by electro-magnetic field of reader without relying on inter or external power supply. The former may save power required by reader and ensure longer recognition range while it is limited in runtime and more expensive than the latter. On the other hand, passive type is lighter and less expensive than active type and semi-permanent. But, its reading range is short and requires reader to consume more power. Tags are also classified by their frequency band as tag characteristics vary, depending on radio frequencies used. Frequency band in most use are: 125.134KHz, 13.56MHz, 433MHz, 860~960MHz, and 2.45GHz.

2.2 Limitations of RFID

1) Non-Standardization & High Cost

Readers, tags and SW applications available in the market are hardly compatible with each other. Each vendor is concerned that its own technical result may be disclosed to competitors. Accordingly, compatibility issues across RFID frequency ranges, components, active/passive tags, data structure, data classification & representation, communication protocol between tag and reader are the bone of contention in a debate on standardization of RFID systems.

Moreover, utilization of RFID system is not commonly available for its high cost. It is difficult to expand the scope of RFID application at the moment for price of tag is still too high, but it is believed to become affordable in several years given the rapid development of applicable technologies.

2) Metal & Frequency Interference

Obstructions to recognition of information stored in RFID tag are broken down to two categories. First of all, metallic materials reflect RF signal, interfering tag antenna with radio reception. Next is the assignment of frequency band which is delayed at the moment, obstructing spread of RFID products. In other words, it is yet difficult to discern various data in the same frequency band. Governments are trying to define assignable frequency band in legislation. In addition, rubber or liquid such as water also interferes with reception of RF signal.

2.2 Application of RFID Technology in Constructions

A domestic construction contractor implemented a labor and material (ready mixed concrete) tracking system utilizing bar-code platform which is a predecessor of RFID technology and saved about KRW 4.1 billion in direct and indirect costs and 1 month in construction schedule, which implies that RFID technology that is more advanced than bar-code approach may ensure better returns when applied.

The U.S. Carnegie Mellon University proposed a precast concrete material tracking system utilizing RFID platform [2]. $178,000 (equal to 7,120 working hours) was invested in RFID system implementation in total, but time spent on tracking materials was cut in half. The system is also thought to lead to additional cost saving as cost overrun incurred by delays in material delivery is estimated at $60,000 per supplier every year.

A site test of the Construction Industry Institute (CII) of the U.S. conducted in the Red Hills Construction Project of Bechtel found out that RFID technology saved time spent on locating and tracking pipe supports and hangers by 30% (159 min./100 hangers) [3]. In other cases, RFID technology was pilot tested to locate and track compressed gas cylinder, small tools or construction equipment and feasibility of applying RFID systems to detect fatigues of excessive stress to concrete and steel components to support structural maintenance is being studied.

RFID technology is not widely used in the domestic construction industry. As mentioned before, some general contractors applied bar-code technology to labor and material management in a limited scope to a certain degree of success, but limitations of bar-code technology such as data recognition error or limited reading range revealed several problems in actual implementation. However, radio frequency recognition technologies such RFID systems may promise significant returns on investment if their advantages are properly utilized,

which will mark a great turning point in application of IT technology in construction industry.

2.3 Application Procedure of RFID

Users of RFID system must base its design on major considerations at each stage of system implementation. First of all, purpose of RFID implementation must be clarified whether it is time saving, material tracking or equipment control, etc. Next, it should be determined whether the system would provide simply Read Only (R/O) or Read/Write (R/W) function would be required. The latter may be desirable if tag data contents are to be modified after implementation from time to time and the former may be acceptable if that is not the case. Then, database capacity should be defined. If data storage capacity is less than 2kbytes, R/O system is recommended and R/W system if it is the other way around. In addition, potential interferences with RF signal need to be considered in system design [4].

Table 1. Important Considerations on RFID Technology [3]

Category	Considerations		
[1]	Types of Field of RFID Application		
[2]	Change Tag Contents: R/O or R/W		
	R/O RFID System	R/W RFID System	
[3]	Data Capacity		
[4]	Data Format(R/O, R/W)		
	All data on tag(R/O, R/W)	Unique ID(R/O, R/W)	
[5]	Data Security(R/O, R/W)		
[6]	Reading Ranges & Tag Frequency		
	0~1centimeter	0~1meter	>1meter
[7]	Encapsulation: Tag Protective Enclosure		
[8]	Metal Inference		
[9]	Reader: Handheld or Stationary		
[10]	Anti-collision Capability		
[11]	Frequency Inference		
[12]	Integrate into PMIS (Project Management Information System)		

Notably, metals interfere with RF signal easily and frequency range is also critical, as the system is required to discern lots of signals contained in a single frequency band. In addition, whether to use fixed reader or portable type and whether RFID system needs to be integrated with project management information system (PMIS) should be reflected on system design (Table 1).

2.4 Material Management Process in Construction

1) Property of Procurement Process

Construction material management is exposed to lots of exceptional influences and difficulty of accurate estimation since site conditions vary from site to site and construction progress may be hard to forecast accurately, depending on characteristics of the site. There are also lots of potential risks subject to changes in environment. Therefore, it is hard to plan material management in a long term and control materials in a systematic manner aligned to varying local and site conditions. On top of that, traffic congestion often delays material delivery in high-rise building construction sites located downtown. Construction materials are contracted, ordered, manufactured, delivered, moved to location, and installed to build. Speaking of tasks in detail of each step in the aforementioned flow, material quantity, construction schedule, packaging method, transportation arrangement and on-site moving method are determined at contracting step. In the following ordering and manufacturing steps, specific procurement approach and detailed production plan are defined. At transporting step, required quantity considering loss in storing and transportation/ on-site moving units is determined, part/material data is recorded and material specification/invoice is provided. In storing phase, storing location is confirmed and storing information is recorded and then materials are either stored or moved to location in accordance with stock after delivery or lift up upon delivery principle.

2) Material Management Process of Finishing Material

Problem of as-is material management process is such that most of the material control is exercised by head office and procurement data is not stored, making it difficult to make a timely decision. Also, focus of material management is placed only on material flow while interface to cost or schedule control is not properly emphasized.

Some general construction contractors have implemented project management information system (PMIS) or adopted supply chain management system (SCM) of manufacturing industry to improve effectiveness of construction control, but as data and information generates is not accumulated, improving construction control capability is not easy yet. Therefore, this research attempts to design a RFID-based material tracking system capable of providing real time inputs to the end-to-end material management flow ranging from data generation to utilization and analysis with focuses on shipment of finishing material by supplier, tracking and locating such material on site.

3. Finishing Material Selection

3.1 Background

It may vary from building to building, but approximately 1,000 different materials are usually required in high-rise building (> 45 floors) construction projects. Especially, about 100 materials are required in structure work while the remaining 900 materials are used in finishing-work stage. Construction materials vary in type, shape and dimension and each material is procured, transported, delivered, moved and delivered in a different manner. Therefore, it is not practical to develop a material

management plan considering all those parameters. Hence, several finishing materials that are easy to monitor with RFID material tracking system were selected in consideration of pre-conditions to application of RFID technology following literature reviews and interviews with industry experts.

3.2 Selection

Ahn(2003) proposed concepts of representative finishing materials to examine feasibility of finishing material moving plan in high-rise building construction and selected 9 representative finishing materials (gypsum board, stud, ceiling material, lightweight steel frame, rock wool, floor tile, stone, curtain wall and duct) [4]. As major finishing materials were already identified in a preceding study, we narrowed down on the scope of finishing materials application to this study from the 9 materials in consideration of inputs from the other experts.

After interviewing with experts over 10 representative finishing materials, interviewed project managers suggested that, given the known factors that may limit effectiveness of RFID technology such as material characteristics (radio interference), packaging and dimension and field requirements for RFID system, priorities be given to finished products that are not required to be assembled on site and materials shipped in boxes or pallets by suppliers to ensure effectiveness of RFID application. In that context, ceiling material shipped as packaged in boxes was selected as a candidate to which our RFID-assisted material tracking system model would be applied.

3.3 Material Management Process of Ceiling Materials

In consideration of the major concerns for application of RFID technology as described in the above and specific tasks of procurement process, type, size and packaging unit applicable to ceiling material, material tracking system model was developed.

1) Procurement Process

Materials manager procures materials in reference to basic parameters of material management such as delivery timing and stocking standard. Weekly plan is developed in a weekly working schedule meeting with supplier representatives and construction managers at site office and construction site manager forwards material management information to integrated logistics team to adjust material delivery order among construction sections and sends purchase order to supplier. Based on the purchase order, material supplier issues invoice where project site name, construction section, access point and supplier name. Site materials manager confirms invoice and inspect delivered material (Fig. 2).

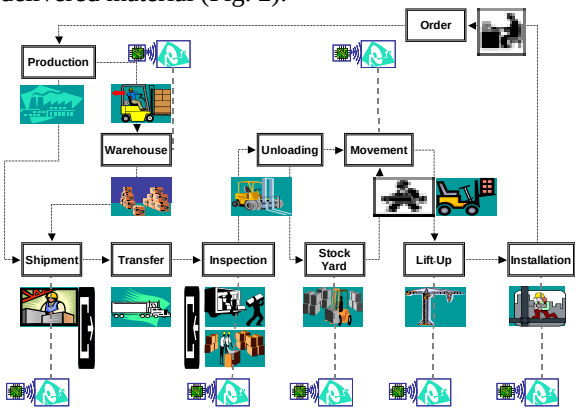

Figure 2. RFID Material Management Process Concept of Ceiling Materials

2) RFID Application of Material Tracking System

Given the characteristics of finishing work, even materials of the same nature may have a variety of shapes or types, a lot of material data is required and linked to cost, such data needs to be assigned with unique ID when stored in tag. Given the considerable needs of large quantity of data for system operation, it may be sensible to store some information such as construction site name in tag without assigning unique ID so that it can be confirmed right away on the spot [5].

Table 2. Application Procedure of RFID system [3]

Category	Requirements		Choice
Change Tag Contents	**Read Only:** Cannot be altered/ 135KHz~2.45GHz frequency range		√
	Read Write: Rewritable(Can be altered)		
Data Capacity	**Read Only:** Store a limited amount of information(<2kbytes).		√
	Read Write: High Memory(16 kbytes)		
Data Format	Storing all of the data on tag		
	Programming a unique ID-number		√
Data Security	**NO: Read Only**		√
	Yes: Read Write(135kHz, 13.56MHz, 27.125MHz, 2.45GHz).		
Reading Ranges & Tag Frequency	0~1cm	Close Coupling System(30 MHz)	
	0~1m	<135KHz, 6.75MHz, 13.56MHz, 27.125MHz, 2.45 GHz(contactless smart cards, material tracking, animal identification, and timekeeping)	
	>1m	900MHz, 2.45GHz, 5.8GHz, 24.125GHz -Passive tags or Active tags	√
Metal Inference	**No:**		√
	Yes: metal may be one material that can cause interference.		
Reader: Handheld or Stationary	The handheld readers offer portability(Material management)		√
	Stationary devices offer a larger reading range(turnstile to enter the jobsite, facility entrance)		
Anti-collision Capability	**No:** Do not consider anti-collision procedures		
	Yes: Other considerations relate to tags being spaced closely together.		√
Frequency Inference	**No:** Select most expedient frequency		
	Yes: Identify and avoid conflicting transmission frequencies		√
Integrated into PMIS	**No:**		
	Yes: It is very important to have this RFID system compatible with the PMIS(Project Management Information System)		√

Since working environment is not that favorable in most construction sites, passive type tags with reading range of 3~10m may be adequate for finishing materials delivered in large quantity. Also finishing materials are usually delivered in large quantity to site at once, it can be difficult to read tags attached to packaging boxes as they are stocked close to each other. Therefore, program to be developed must be capable of preventing collision between data signals. Radio interference by other electro-magnetic waves should also be considered. Standardization of

frequency ranges assigned to each RFID type are yet to be determined in Korea, but 900MHz believed to be adequate for material tracking system was selected tentatively for this research. Tabe2 is a checklist filled out to develop finishing material procurement process utilizing RFID technology.

3.4 RFID Material Tracking System Modeling

1) Work Flow in Material Tracking System

In reference to RFID design checklist, box-packaged finishing material procurement process and tag-stored data are identified in the following figure. In general, standardized products in great demands are delivered to site after being stocked in stockyard (warehouse) or right away if urgently needed. Given that, two site delivery flows were defined. In addition, lift up flow was also defined to have double track as some materials are stocked (assembled) on site and lifted up to floor while others are lifted up upon delivery to site.

This research adopted 900MHz passive R/O tag for RFID-assisted material tracking system model. As shown in the conceptual diagram of Figure 3 readers were not proposed for movement and lift up/stocking steps but applied to the other steps as in the material procurement process concept. Data inputs to the finishing material tracking system were defined in a series of interviews with site engineers.

Table 3. Entity & Attribute of System

Entity	Attribute
Production	Field ID, Field Name, Address, Product Date Field Summary, Owner, Designer, Supervisor, Engineer, Commencement Date, Project Schedule, Completion Date, Phone No.
Supply (Shipment & Warehouse)	Material ID, Vehicle No., Vehicle Capacity, Driver Name, Supply Date, Supplier Name, Invoice No., Material Transfer Time, Gate No. Stockyard No. Recipient
Supplier	Supplier Name, Mgr Name, Address, Tel No.
Field	Field ID, Field Name, Address, Field Summary, Owner, Designer, Supervisor, Commencement Date, Completion Date, Phone No.
Building No.	Field ID, Building No., Zoning No.
Floor	Field ID, Building No., Zoning No., Floor No.
Material (Ceiling Material)	Material ID, Type, Size, Color, Unit, Installation, Building No., Floor No.
Production	Material ID, Product Name, Product Date, Related DWG.
Inspection & Unloading	Vehicle No., Driver Name, Invoice No., Inspection Date, Inspector Name, Stockyard No. Lift-up Qnty., Stockyard Qnty.
Lift-Up	Field ID, Building No., Zoning No., Floor No., Material ID, Lift-up Date, Lift-up Qnty., Sub-con Name, Hoist No., Worker. Lift-up Method, Mgr Name, Engr Name
Reservation	Floor No., Supply schedule, Lift-up schedule, Install Schedule, Material ID, Material Qnty., Lift-up Qnty., Hoist No., Engr Name
Stockyard	Zoning No., Stockyard No., Material ID, Material Qnty., Material Qnty., Inventory Qnty. Worker
Order	Field No., Building No., Zoning No., Gene-con Name, Engr Name, Material ID, Material Qnty., Material Qnty., Supply schedule, Supplier Name, Inventory Qnty. Project Schedule, Cost ID, WBS ID, Work Package ID, Lead Time, Change Order, Engr Name
Gene-Con	Field No., Gene-con Name, Mgr Name, Engr Name, Tel No.
Sub-Con	Field No., Sub-con Name, Mgr Name, Tel No., Gene-con Name

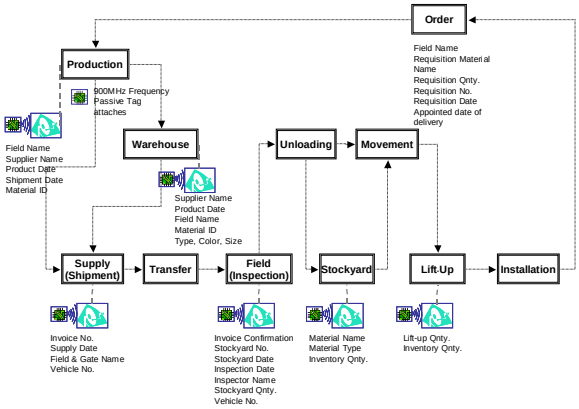

Figure 3. Supply and Moving Process for Material Tracking System

4. System Modeling

4.1 Database Flow Diagram

To develop a pilot material tracking system, following data flow as in Figure 4 was proposed. Data attributes of material management process was grouped by site manager, material engineer, manufacturer and material supplier and interface to scheduling information was defined in the data flow. Material code was derived from the Standard Product Breakdown Structure of MOCT and product code and supplier code were specified in the database.

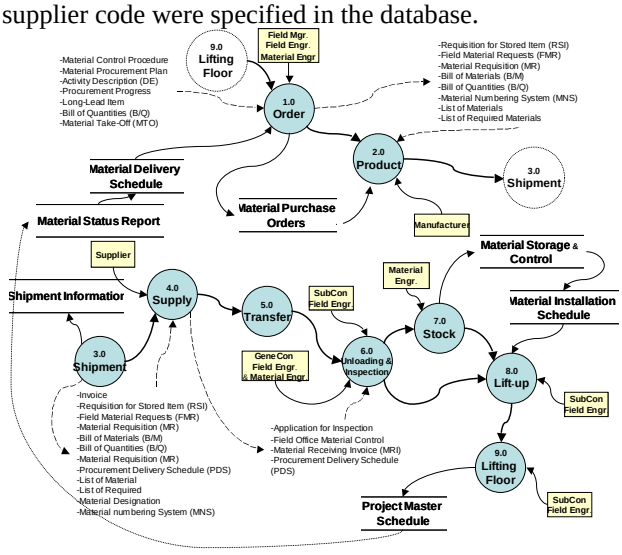

Figure 4. Database Flow Diagram of Material Tracking System

4.2 Database Modeling

Based on representative data attributes applicable to ceiling material tracking system development as in Table 3, data attributes were grouped per entity and workflow definition was transformed into database model (Figure 5). This research has simply focused on describing parameters required for implementation of RFID-assisted finishing material tracking system and effectiveness of RFID employed in material management system

compared to that of conventional material management process has yet to be verified in specific site tests.

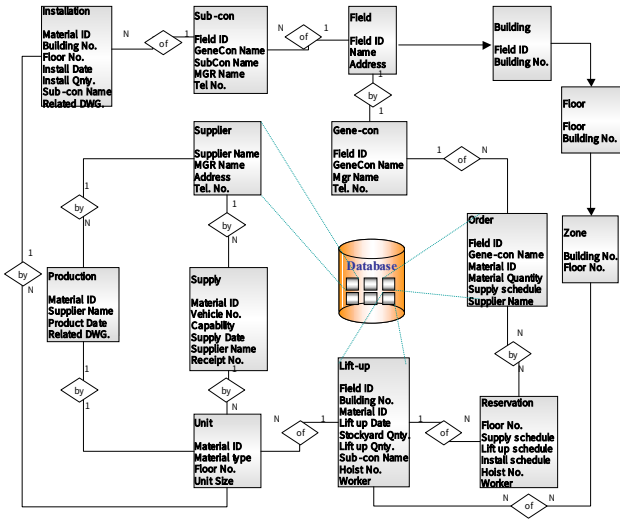

Figure 5. Database Model (Entity-Relationship)

5. CONCLUSIONS

Sensing technology is expected to bring considerable benefits to construction industry, but there are still potentials to be developed in terms of applying and utilizing it for specific purposes. While other industries are technically advancing at a rapid pace and trying to innovate manufacturing process, construction industry is still locked with conventional approaches and return on investment is not very high.

Construction industry should be reshaped by innovative technology platforms such as RFID. The finishing material tracking system proposed herein should be further refined and verified in the future so that it may provide a momentum for driving changes of construction industry and a drastic shift in mindsets of those engaged in construction industry is called for.

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A WEB AGENT FOR CONCEPTUAL COST ESTIMATION OF HIGHWAY CONSTRUCTION PROJECTS

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Abstract: Accurate cost estimation in the early stage of project lifecycle is essential for both effective financial planning and cost control of construction projects. Previous efforts by the research team have developed a Web-based Intelligent Cost Estimator (WICE) system. This paper describes a further step of WICE research to develop a special-purpose web agent for various highway construction project participants to utilize WICE. The proposed system has shown improvement on the usability of WICE so that even users without estimation knowledge can utilize the functions provided by WICE.

Keywords: Web agent; Neuro-fuzzy; Conceptual estimation; Highway construction; WICE.

1. INTRODUCTION

The cost estimation in conceptual planning phase provides the foundation for both effective financial planning and cost control of construction projects. However, accurate cost estimation is hard to obtain before the detail design due to the complete design information is not available at that stage. In order to improve this problem, many conceptual cost estimation methods have been proposed including statistics based methods (e.g., unit-area method, unit-volume method, unit-capacity method, etc.), principal items method (e.g., principal material items method and principal activities method), cost index method, and parametric estimation method [1]. Among the above conceptual cost estimation methods, parametric estimation method has been proved capable of generating accurate estimates comparable to the results with detail estimation method [2,3]. As a result, the research team developed a Web-based Intelligent Cost Estimator (WICE) [4] to meet the needs of the construction industry.

The WICE system is based on a previously proposed PIREM (Principal Items Ratio Estimation Method) [1], which combines the Principal Items Method and Parametric Estimation Method to form a new conceptual cost estimation method. Another feature of WICE is the integration of a neuro-fuzzy artificial intelligence technique and the web based information technology to provide a web-based intelligent cost estimation system. The WICE system provides many desirable features for construction cost estimation such as real-time estimation function, sensitivity analysis function, low maintenance cost, global accessibility, and high estimation accuracy. However, the WICE requires users to input values of influential attributes for various types of construction projects. Such attribute values are based on the "engineering judgments" of the domain experts (or experienced engineers). Such requirements have put limitations on the usability of WICE system, since in most cases the decisions during feasibility analysis stage are made by top managers or investors who are not "domain experts" for cost estimation. Moreover, for public construction projects, the budgets should be reviewed and audited by the county councilors, the state assemblymen, or the legislators of the state who are not specialized in construction cost estimation. A need rises to develop a system that can assist the users of WICE in entering attribute values and organizing estimation results, so that users without engineering background can also enjoy the functions provided by WICE.

The paper is presented in the following manner. Literature related to web agents is reviewed first. Then, the framework and functions of WICE system is described in details. In the fourth section, the web agent for highway construction cost estimation is proposed. The system is implemented and testing in Section Five. Finally, conclusions and future works are discussed at the end of this paper.

2. REVIEW OF WEB AGENT

The web agent is an emerging information technology that incorporates World Wide Web (WWW), databases, and artificial intelligence (AI) technologies. This section reviews some literature related to web agent.

2.1 Definition of Web Agent

Nwana proposed three characteristics required for an agent [5]: (1) autonomy—meaning that an agent should act independently in performing their functions without requirement of human guidance; (2) cooperation—the agent should be able to cooperate and communicate with human users or other agents; (3) Learning—the agents should be able to learn

through the interaction with users to improve their performance.

Wooldridge and Jennings [6] defined "intelligent agents" as computer systems that act adaptively and independently to achieve their goals. Sycara [7] gave definition of "intelligent agents" as "a computer system that assistant the human users in time consuming information collection, information searching, and integration of fragmented information", and. Bradshaw considered agent as a system that represents the user to communicate with other system.

Harrison et al. believed that an intelligent agent has the following features: (1) delegation—the functions of agents are determined by the user; (2) communication—the agent should be able to communicate effectively the user; (3) autonomy—even though the functions of agents are determined by the user, the agent should be able to complete its job without directions provide by human users; (4) monitoring—the agent should be able to sense the influence of environmental changes, so that outputs of the system adapt accordingly; (5) actuation—the agent should be able to act according to its reasoning result; (6) intelligence—agent should possesses some sort of knowledge that might be stored in forms of decision rules, patterns, and predetermined procedures; (7) Others.

Bryson et al. defined the term *agent* as any autonomous actor with sets of: (1) goals—conditions the agent works to achieve or fulfill; (2) intentions—goals and sub-goals the agent is currently engaged in pursuing; (3) beliefs—knowledge about the world (which is limited and possibly inaccurate); and (4) behaviors—actions the agent is able to take.

2.2 Review on Web Services

Web services are application programs that users can access and execute via internet without the installation on the client's platform [9]. Thus, the web services basically perform the same functions as PC-based programs. In contrast to the PC-based programs, the web service program does not execute on the client's PC, but on the server. Different from web pages, web services are not merely an information bulletin that provides static information. It interacts with the users and even execute programs including database searching and other computational programs, so that complicated functions can be performed by the web services programs.

Some merits of web services include [4,10]: (1) centralized databases and knowledge bases management—update of database and knowledge base are guaranteed; (2) minimum requirement on client's platform—many application programs require platform system to provide sufficient hardware capacity and capability, web services place hardware and software requirements only on the server, thus save costs for the clients; (3) globally and all-time accessible—web services are opened 24 hrs everyday, users around the world can access the application anytime and anywhere; (4) minimized maintenance costs—the centralized databases and single server system can lower the system maintenance costs.

In spite of the many merits described above, web services also hold several drawbacks, such as (1) requirement of internet connection—the quality and safety of the program execution are relied on the quality and safety of internet connection; (2) security of client's information—many web services require the users to input information of related attributes of the program and even personal information, this may cause security problems of the users' information; (3) requirements on formatted inputs—unlike other web searching engines, the web services require users to input information as the web interface requires, thus the flexibility of requests by the users are limited; (4) system stabilization—the centralized platform may cause problem of stabilization, this can be mediated by back up systems.

3. WEB-BASED INTELLIGENT COST ESTIMATOR (WICE)

In order to meet the requirement of real-time cost estimation, an intelligent web based cost estimation system namely Web-based Intelligent Cost Estimator (WICE) was developed under the collaboration efforts of Chung Hua University and the industrial partner, CHINA ENGINEERING CONSULTANTS, INC. (CECI), Taipei, Taiwan. This section describes the WICE system and its underlying theories in details to provide backgrounds for the development of web agent in this paper.

3.1 Theoretical Backgrounds of WICE

(1) Principal Items Ratio Cost Estimation Method (PIREM)—the essential problem for all analog based cost estimating approaches is that the unit prices of cost items fluctuate as time passes. Thus, construction cost estimates obtained based on previous estimation experiences may be incorrect due to unit price variation in the marketplace. The key problem is the use of "activity cost" as the measure of estimates during analogizing process. In WICE a Principal Items Ratio Cost Estimation Method (PIREM) was adopted to take the "unit price" and "activity quantity" apart in an activity cost item. Previous knowledge acquired from historical data is used to estimate the quantities of an activity. On the other hand, the most updated unit price information is surveyed in the marketplace to reflect the current unit prices of material, labor, and equipment.

In order to simplify and reduce the estimation effort, only the most important cost items are taking into account for cost estimation. Thus, the Pareto Optimum

Criterion (or named "80/20 Principle") is adopted. Simply stated, the Pareto Optimum Criterion suggests that 80% of the overall project cost is determined by 20% of the cost items [11]. Therefore, instead of estimating the quantities of all cost items, only the top 20% most important cost items' quantities are estimated and their related unit prices are inquired. The selected top 20% cost items is called "principal items (*PI*)". The summation of quantities and unit prices of the principal cost items constitutes the cost of principal items (*PIC*). The ratio of *PIC* over the overall cost is defined as the principal item ratio (*PIR* or *p*). The value of *p* can be calculated by the following equation.

$$p^s = \frac{\sum_{j=1}^{l} UP_j^s \cdot Q_j^s}{\sum_{i=1}^{n} UP_i^s \cdot Q_i^s} = \frac{PIC^s}{OC^s}, \quad (1)$$

where the numerator is the summation of the costs of all principal items, while the denominator is the summation of the costs of all cost items in a project. The super script *s* upon all parameters stands for the s^{th} historical example. UP_i means unit price and Q_i means quantity of the i^{th} cost item, and so forth. *OC* stands for overall cost. The ratio *p* obtained in Eq. (1) is call "principal item ratio (*PIR*)" as defined above.

It is found by analyzing *PIR*'s obtained from historical cost estimation data that the *PIR* of a specific type of construction project usually keeps constant with very small variation [1]. Therefore, given the *PIC*, the *OC* of the new project can be recovered by the following equation.

$$OC^r = \frac{PIC^r}{\overline{p}}, \quad (2)$$

where OC^r is the estimate of overall cost for the new (r^{th}) project. $\overline{p}$ is the average *PIR* calculated from previous projects. PIC^r is the cost of principal items of the new (r^{th}) project.

In Eq. (1) and (2), the current unit prices (*UP*'s) for the new project should be inquired from the marketplace at the moment of estimation. While, the quantity, *Q*, and average *PIR*, $\overline{p}$, have to be determined by parametric estimating methods based on the pre-determined mathematic relationships. This relationship should be established according to the knowledge acquired from historical data.

(2) ANFIS neuro-fuzzy data mining—in order to establish the relationship between influential attributes and activity quantities, a neuro-fuzzy data mining technique named ANFIS [12] was adopted to mine estimation knowledge from historical data. Figure 1 shows the architecture of ANFIS network, where the network consists of 6 layers: (1) Layer 0—input layer; (2) Layer 1—membership functions; (3) Layer 2—t-norm operation; (4) Layer 3—normalization of inference output; (5) Layer 4 Sugeno FIS (fuzzy inference system) operation; and (6) Layer 5—aggregation operation for output.

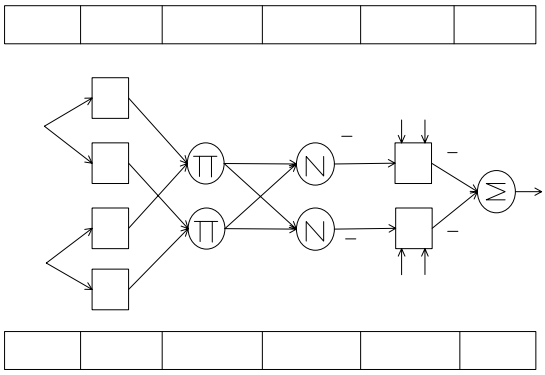

Figure 1. ANFIS network architecture [12]

The Sugeno FIS operation adopts a linear function in the consequence of a fuzzy decision rule, so that the defuzzification of FIS becomes straightforward. From extensive application testing results, it was found that ANFIS is extraordinarily excellent in mining nonlinear relationships existing in the historical databases [2].

3.2 Framework of WICE

The Matlab 6.3 with Web Server and Fuzzy Logic Toolboxes is adopted for WICE development. The platform selected for WICE implementation consists of: (1) PC CPU: Pentium IV 1.5G; (2) OS: Windows 2000 Server; (3) SRAM: 1.0 G. Since the ANFIS trainings can be done offline, the CPU speed for the web server may be not demanding. However, broader bandwidth for transmission is required if the number of simultaneous accesses or need on graphic transmissions is large. The framework and data flows of WICE are depicted in Figure 2, where the Client (User) *A* submits parameter inputs (including influential attributes and unit prices) and job request to WICE by filling out the Parameter Input Sheet. The WICE then transmits the input data to Matlab main system via the interface and web-server programs. The Matlab main system consults related Matlab programs and performs the required calculations (including ANFIS network mapping), and then the results (including estimation results and relevant graphics) are generated. The numeric data (resulted estimates) and graphics are handled

separately hereafter. The numeric data are transmitted backward via web-server and interface programs to the respond form of the Client. In the meanwhile, generated graphics (if applicable) are loaded on the respond form. Thus the request of Client *A* is completely served. Multiple requests by different users are served simultaneously via the similar process for Client *A* described above, while buffer of memory (i.e., capacity of RAM) for storing intermediate data is required as the number of simultaneous users increases. The intermediate data are handled by the web server and interface programs so that no conflict occurs while multiple users are accessing WICE.

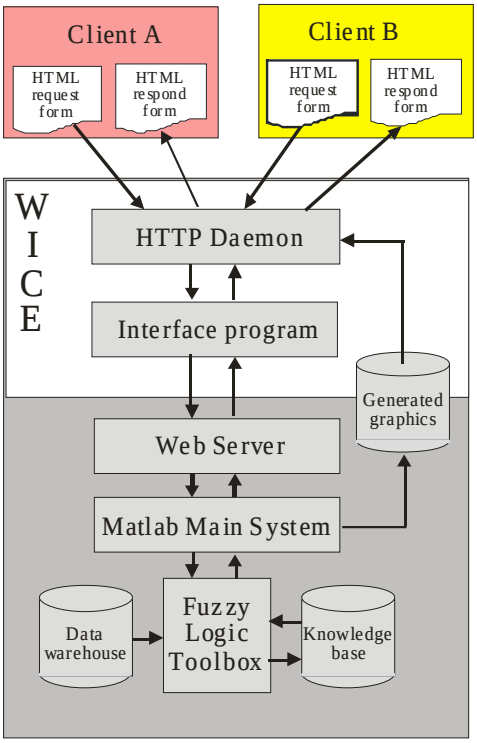

Figure 2. Framework and data flows of WICE [4]

4. PROPOSED WEB AGENT FOR HIGHWAY CONSTRUCTION COST ESTIMATION

This section proposes a web agent for highway construction cost estimation based on the WICE system described in the previous section.

4.1 Highway Construction Cost Estimation Process

The cost estimation process for highway construction projects using WICE system is studied by interviews with domain experts of CECI [2]. The resulted process is depicted in Figure 3. The process consists of three major steps: (1) collecting basic information regarding to the influential attributes based on the SPEC's and drawings; (2) estimating the values of influential attributes based on the judgments of domain experts or applying expert rules; (3) entering the values of influential attributes into WICE system and presenting the estimation results.

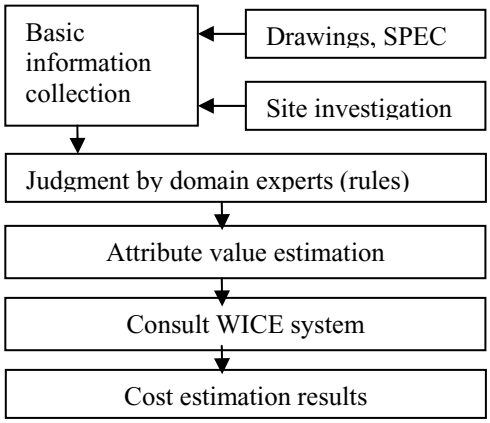

Figure 3. Process of highway construction cost estimation with WICE

4.2 Knowledge Base of Web Agent

The key for the "intelligence" of the web agent is the underlying knowledge stored in the knowledge base. In this case, the knowledge of the domain experts is stored in terms of IF-THEN rules. In this research, totally 65 IF-THEN rues were generated through interviews with experiences estimators. These rules are stored in the form of decision tree. Figure 4 is a part of the such decision tree.

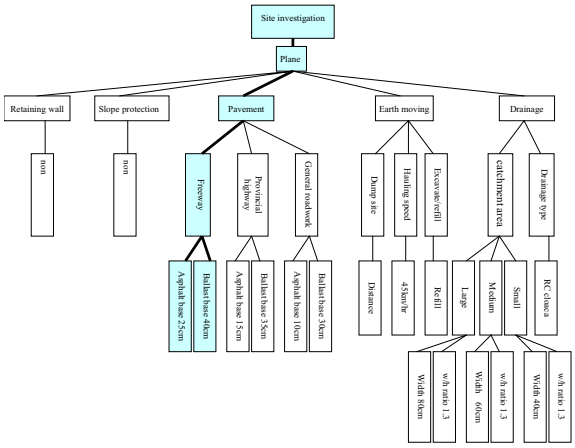

Figure 4. Part of the decision tree for IF-THEN rules

The shadowed boxes show two examples of such IF-THEN rules:

Rule #1:

"IF **Site** is ***Plane*** and **Class** is ***Freeway***,
THEN **Asphalt** is ***25 cm*** for Pavement".

Rule #2:

"IF **Site** is ***Plane*** and **Class** is ***Freeway***,
THEN **Ballast Base** *is* ***40 cm*** for Pavement".

In the "IF-part" of the example rule, the underlined terms are names of factors that affect the influential attributes, the italic terms are values of the such factors. In the "THEN-part", the underlined terms are names of the influential attributes; the italic terms are values of the attributes that are generated by the rules.

4.3 Framework of Web Agent

Framework of the proposed web agent system is shown in Figure 5. The usage process of the proposed system consists of 6 steps: (1) assessment of attributes—by the process shown in Figure 3; (2) collaboration with various agents in WICE—to generate estimation results for each activities; (3) presentation of the estimation results to user; (4) evaluation of the estimation results by domain expert—if the results are approved, the estimation results are accepted and stored in the historical database as a new data, otherwise are expelled; (5) training of knowledge base—after a period of time, the knowledge base is updated by system training; (6) update of knowledge base of each agent.

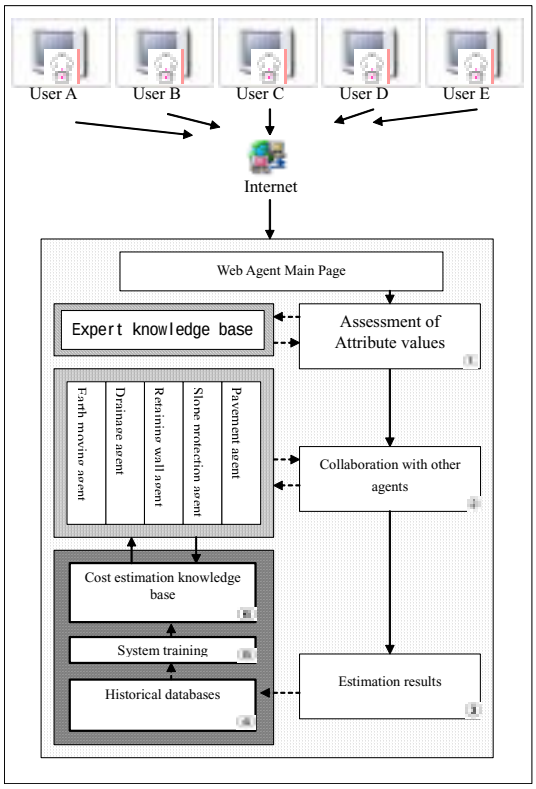

Figure 5. System framework of proposed web agent

5. SYSTEM IMPLEMENTATION AND TESTING

The proposed web agent for WICE system to facilitate various users of highway construction project participants is implemented as a web interface that dynamically interact with the users and WICE system to acquire required information for conceptual cost estimation, and provide collective information of estimation results.

The implemented system is shown in Figure 6~9. The primitive version of the proposed system is developed in Chinese language. Figure 6 shows the main page of the proposed web agent. Figure 7 shows the web page acquiring basic information from the user. In Figure 7, the basic information is in forms of questions of common sense, so that users who are not experienced estimators can also answer the questions. Should the user be not able to answer the question, the system provides default "best guess" solution of the user.

Figure 6. Main page of proposed web agent

Figure 7. Web page for basic information collection

Figure 8. Attribute values estimated by expert rules

Figure 8 shows the results of the estimated attribute values obtained by the system after applying expert rules. Up to this stage, the required input

attribute values are generated. In Figure 8, the user is allowed to fine-tune the estimated values by directly entering his/her values.

The final step is to generate the overall estimation results by collaboration of various agents of WICE, including Earth moving agent, Drainage agent, Retaining wall agent, Slope protection agent, and Pavement agent. The attribute values are passed internally in WICE to the above mentioned agents. The estimation results of each agent are generated and shown in Figure 9. The overall project cost estimation is also shown on the top in Figure 9 to provide final estimation result for the user.

Figure 9. Presentation of estimation results

With aids of the proposed web agent, even inexperienced users can fully exploit functions provided by WICE. Real world examples of highway construction projects have been tested in the implemented web agent to verify the system. Due to the limitation of the paper, the testing process is not shown here. However, the results show that the proposed system can generate identical results as the domain experts do using WICE.

6. CONCLUSIONS AND FUTURE WORKS

This paper presents a web agent for cost estimation of highway construction projects. The proposed system is an extension of previous research—Web-based Intelligent Estimator (WICE). The proposed system integrates WICE with the knowledge of domain experts to provide users, who are not experienced cost estimators, an assistant for using WICE system. The proposed system is implemented and tested with real world example projects. It is found that the proposed system can generate cost estimation result similar to the domain experts while using WICE system.

Future directions after this research include (1) automated learning process of expert knowledge base for acquiring information provided by the users; (2) application of same methodology to build agent for other type of works; (3) more on the domain knowledge acquisition that is not fully researched in this paper.

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FIELD TRIALS OF RFID TECHNOLOGY FOR TRACKING PRE-FABRICATED PIPE SPOOLS

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Abstract: The FIATECH Smart Chips project, in conjunction with Shaw Pipe Fabricators and Fluor Corporation, undertook field tests of current RFID technology to determine its technical feasibility for automatically identifying fabricated pipe spools in a laydown yard and tracking shipment through portals. The results indicate the technology could work effectively in the field environment and that it has reached the stage where it can begin to be used to reliably track materials through major portals. Currently, the authors are assessing its potential economic benefits based on preliminary information on recent industrial projects and data provided by the literature.

Keywords: Automated Data Collection, RFID, Technical Feasibility, Materials Management.

1. INTRODUCTION

Of the elements that comprise a constructed facility, construction materials may account for 50-60% of the total cost of a construction project. Materials for a construction project can be classified into three categories: off-the-shelf, long-lead bulks, and engineered items [1]. The different categories of materials vary in cost, delivery lead time, and interchangeability. Generally, engineered items are available at higher costs in smaller quantities and with more unique properties, thus implying longer lead time and requiring more front-end planning.

1.1 Piping Function and Practice

Among engineered materials, pipe spools are of particular interest to industrial projects as piping has been recognized as a very critical yet most costly and least efficient process [2]. Industrial process facilities often involve hundreds or thousands of pipe spools, many of which are unique in material (e.g., cast iron), shape, finish, and other properties (even final installation location on site). In an average size (US$200-300M) industrial project, there may be as many as 10,000 pipe spools [3].

Many industrial projects are on fast-track, due to the pressing need to bring products to the markets fast. Given this characteristic, some industrial projects may take the opportunity to fabricate pipe spools off-site while prerequisite works on site are making progress. In fact, piping has seen significant increase in the use of prefabrication and preassembly over the preceding twenty years [4]. However, piping in fast-track projects still poses potential uncertainty in deliveries and in completing prerequisite site work, leading to "mis-matches that foul up scheduled work sequences" [2].

Under this uncertainty, materials managers rely on large buffers of pipe spools in an effort to secure flexibility in workable backlogs so that they have "at least 60 percent of all pipe on site when 20 percent of the pipe had been installed" [5]. Such large buffers of pipe spools are built in a constructor's laydown yard from deliveries received 5 to 6 months prior to scheduled installation, and received pipe spools reside in the laydown yard until requisition from pipe fitting crews.

Ultimately, laydown yard personnel will find and stage requisite pipe spools to the crew's work area for installation. In some cases, they may not be able to locate pipe spools in the laydown yard within a reasonable time and have to search for the "misplaced" pipe spools not only in their own premises but also, for instance, in pipe fabricator's storage areas. Misplaced pipe spools for a single project may only amount to 2 percent of all pipes [3], but this turns out to be 200 pipe spools for the average size industrial project involving total 10,000 spools.

1.2 Potential Enabling Technology

In the context described above, it is not surprising that field materials management was identified by a recent construction technology needs assessment as one of the areas with the greatest potential for improvement and the greatest positive development impact on engineering construction work processes [6]. Another study supported the notion that RFID (Radio Frequency Identification) technology may assist in streamlining the material management process in the construction industry, although use of the technology in several pilot tests was confined to material receiving at laydown yards [7].

Like barcodes, RFID is an automated data capture (ADC) technology for identifying, locating, or tracking objects or assets and people, but presents several advantages over barcoding in that it does not require physical contact, line-of-sight, or clean

environments devoid of noise, contaminants, glare and dirt.

RFID technology has already seen significant beneficial applications in manufacturing, retailing, and transport and logistics industries [8]. Meanwhile, recent developments in RFID technology have addressed many of the technical limitations that prevented it from working effectively in the construction field environment.

2. OVERVIEW OF FIELD TESTS

In response to the compelling opportunity presented in recent construction industry research and recent advances in RFID technology, the FIATECH (Fully Integrated and Automated Technology) Smart Chips project, in conjunction with Shaw Pipe Fabricators and Fluor Corporation, undertook the field tests of current RFID technology. The primary objective of the tests was to determine the current technical feasibility of using RFID technology to automatically identify fabricated pipe spools (and other information about them) in a laydown yard and through a shipping portal as part of realistic transport environments.

The field tests were conducted in two phases that span from September 2003 to March 2004, to allow a staged assessment of RFID capability in field construction application. Phase I was intended to document technical issues and learning related to the envisioned applications of RFID technology. Based on the findings of Phase I, Phase II was conducted to determine the reliability of RFID technology to automatically identify individual pipe spools as they pass though portal gates in typical transportation conditions (flatbed trailer shipments).

There were many technical issues critical to the construction application to be addressed, including: 1) the RF signal read ranges, which typically need to be longer than in current common commercial RFID applications, 2) metal interference, which has been a problem in many common RFID applications, 3) tag attachment to pipe spools and density (reading signals from many tags in a congested area), and 4) inability to control the position of RFID tags relative to the readers. In order to best assess the capabilities of RFID technology in addressing these issues, recently developed active (as opposed to passive) RFID systems were tried throughout the field tests.

3. DESCRIPTION AND RESULTS OF PHASE I

The Phase I trials were conducted using two different types of RFID systems, equipped with handheld and fixed readers. The handheld system was used in determining the ability to read signals at long distances and around metal in manual receiving and inventory applications. The handheld reader included a reader in PC card format and an antenna that were inserted in a handheld PC and could be carried around a laydown yard or flatbed trailer (see Fig.1).

Figure 1. Handheld reader unit

Confirming that read distances and metal interferences could be addressed, a fixed reader system was installed on a portal structure through which a flatbed trailer could be driven, simulating a typical pipe spool transport and receiving application (see Fig. 2). Description of both RFID systems used in Phase I is summarized in Table 1.

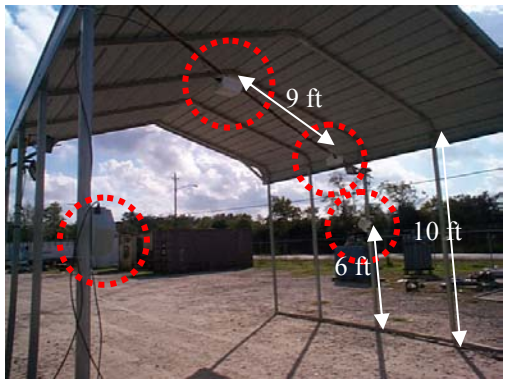

Figure 2. Portal with fixed readers installed

The general test procedure was 1) to have fabrication shop workers place fabricated pipes in a laydown yard and on a flatbed trailer, as they would normally do prior to shipping, 2) to attach RFID tags to individual spools using plastic tie wraps or double sided mounting tape, and 3) to have each RFID system collect unique ID and other information about individual pipe spools when either: a) the handheld

Table 1. RFID technology used in Phase I

	Handheld system	Fixed reader system
Reader (frequency; max. read range)	915 MHz; 20-300 ft depending on types of tags	433.92 MHz; 150 ft
Tag (memory cap.; total no. attached)	64 byte; 12 each	500 KB; 20 each
	8 KB; 12 each	
Tried field conditions	In a laydown yard; around a flatbed trailer while loading pipe spools	While a pipe loaded trailer passed through the portal

reader was carried around about 2-3 ft above the pipe laid down in the yard or loaded on the trailer, or b) the trailer was driven through the portal structure.

For the field trials using the handheld system, RFID tags were attached to 12 individual pipe spools in a variety of sizes and shapes so that most of them were positioned where readers would not be in direct line of sight and/or tag RF signals could be more difficult to reach the readers during the tests (e.g., under large pieces, or on very congested pallets). The results of field trials using the handheld system indicated that current active RFID technology could function well enough in a congested, highly metallic environment to improve efficiency in manual receiving and inventory applications where relatively long read range is desirable. The only difficulties in reading tags in the trials seemed to develop when either: 1) tags were fully surrounded by solid metal (e.g. placed more than an inch or two inside of a spool, or shielded completely by multiple layers of spools), especially with the reader's RF power lowered, 2) or tags were placed in full contact with a surface such as flat metal plate, concrete beam, and the ground. Detailed test logs can be found in [9] that record each trial of reading tags with different placement under varying RF power.

For the field tests with the fixed reader system (or "portal" system), 20 RFID tags were attached to fabricated pipe spools after quality inspection, and loaded on a flatbed trailer to be driven under the portal equipped with four readers (Fig. 2). In addition to the unique ID number of tag, such data as piece marked number, spool number, sketch number, and purchase order number for each pipe spool had been written to tags. The tests were conducted under presumed shipping en route to a construction site, with varying conditions; 1) the density of tags on the trailer, 2) the amount of tag data to be captured - ID only or additional data mentioned earlier, 3) movement of trailer under the portal - pass through or stop-and-go at different speeds, and 4) the number of readers activated - all of the four, those two on top or side, or only one on top center of the portal.

Though limited to general understanding of performance of portal systems, the results of field tests indicated it is technically tractable using current RFID technology to automate tracking the shipping and receiving of fabricated pipe spools beyond simple identification, in typical transport conditions. In the field trials, ID and other information about pipe spools were captured from more tags when the trailer stopped for a short time under the portal, allowing the readers more time (if in order of seconds) to read data. Using multiple readers seemed to be helpful in collecting all tag data, but one reader on top center was sufficient for identification purpose only, provided that the trailer stopped under the portal and then proceeded slowly through it. For more information on the field tests, see [9].

4. DESCRIPTION AND RESULTS OF PHASE II

Phase I has addressed many technical issues related to applications of current RFID technology in shipping and receiving the deliveries of pipe spools, and indicated further trials were warranted. Phase II was pursued to determine the reliability of the technology in such an application that would enable automated identification of individual pipe spools as they pass through a portal, or "portal" application, to some statistical significance. Phase II field trials were conducted using a fixed reader system with the same types of tags as in the handheld system of Phase I, but with a fixed reader (Fig. 3) connected to each of four directional antennas on a portal. Detailed description of the technology used in Phase II can be found in [3].

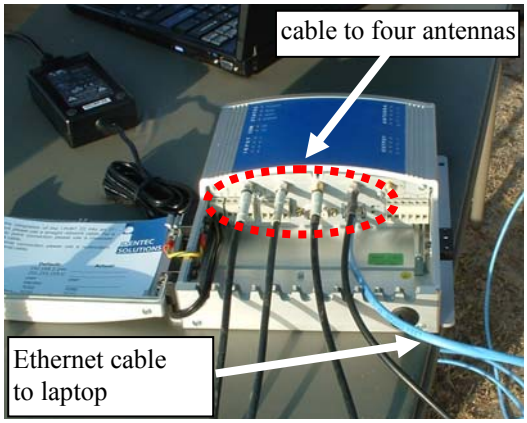

Figure 3. Fixed reader used in Phase II

The Phase II test procedure involved the set up process similar to that of the portal system in Phase I, and testing technical performance of the technology started by determining values of several parameters that form a particular set of field conditions. The test parameters supposed to have some impact on technical performance included those for the fixed system in Phase I, and can be divided into two categories, according to the relative degree of freedom to change their values, as shown in Table 2. Values of the parameters in category Static are relatively hard to meaningfully change since it would not only require much time and effort but affect the fabricator's tight delivery schedule. As such, each parameter in category Static was set to a uniform

Table 2. Categories of Test Parameters in Phase II

Category	Governing level	Test parameters
Static	Test bed	Type and no. of tags Tag positions relative to antennas
Dynamic	Group of trips	Timing of reader activation/deactivation Travel speed of trailer No. of enabled antennas

value over one or two days of field tests, or "test bed", governing technical performance at a high level. Though limited, changing the relative tag positions has been attempted by moving tags around spools or by reversing the traveling direction of the trailer through the portal.

On the other hand, each parameter under the Dynamic category was given different values within a test bed, but expected to have some constant value across a group of trailer passes (or "trips") in the same test bed. For instance, one trip in a test bed was involved with the same type and total number of tags as any other trips in the same test bed, but may be characterized by a different travel speed than some trips in the same test bed.

Phase II have completed four days of field tests and total 70 passes have been made, as shown in Table 3 (superscripts to the total number of tags means different types of tags).

Table 3. Overview of Phase II Field Tests

Test bed no.	Total no. of tags attached	No. of active antennas	No. of trips
1	83^{q}	4	12
2	50^{d}	4	20
3	56^{q}	4 or 2	38
Total			70

In determining technical feasibility of the technology for the portal application, the read rate is used as a metric to assess the ability to identify pipe spools accurately and precisely as the shipment of load departs or arrives through the portal. The read rate measures in percentage how many *different* tags of the total loaded are read in each pass. Since in a single trip, tags could be read more than once via any one of the active antennas, the duplicate read ratio is defined to measure how many times a particular tag is read in each trip. Table 4 summarizes the metrics resulting from each test bed. The median read rate is the 'middle' read rate, so exactly a half of the trips in the test bed resulted in the read rate greater than the median read rate.

Table 4. Summary of Read Rates and Read Ratio

Test bed no.	Mean read rate	Mean duplicate read ratio	Median read rate
1	98.1%	1.4	98.8%
2	96.4%	1.9	98.0%
3	96.0%	6.8	100.0%

Test bed 3 has yielded the minimum mean read rate but the maximum median read rate. The read rate of 38 passes in test bed 3 had the most skewed distribution with several extreme cases (outliers), as can be seen from the box-whisker plot of mean and median read rates in Fig. 4 (means are marked as diamond dots, medians as vertical lines in the box, and outliers as square dots). One possible explanation of this skewed distribution is that test bed 3 has undergone highly dynamic test conditions which arose from parameter values being more actively changed. Test bed 3 also resulted in the largest duplicate ratio, close to 7. It means that if read at all, a single tag was read on average 7 times in each pass. Perhaps, this high duplicate read ratio is due to the reader's RF power set to the maximum that made it so sensitive to RF signals transmitted from tags. By the same token, this may have increased the reader's burden to handle 7 times more data (essentially redundant) received from tags, presumably resulting in the lowest mean read rate.

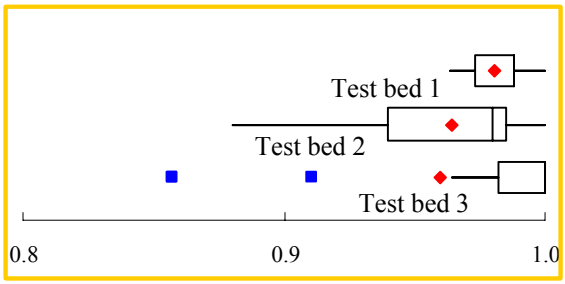

Figure 4. Box-whisker plots of mean and median read rates

Nonetheless, the impact of RF power/sensitivity (reflected by duplicate read ratio) on read rate (or the number of *different* tags read) remains inconclusive, given the limited amount of data. Plotting a pair of duplicate read ratio and read rate for each pass (Fig. 5), it appears that a higher duplicate read ratio is associated with a larger number of *different* tags read, for all the three test beds (the slopes are all positive). Yet this apparent association may not be generalized to say "the more power, the better". Note each test bed involved different values of Static parameters that could not be controlled across other test beds. Indeed, the test bed 3 with RF power set to maximum yielded a lower read rate on average than the other test beds.

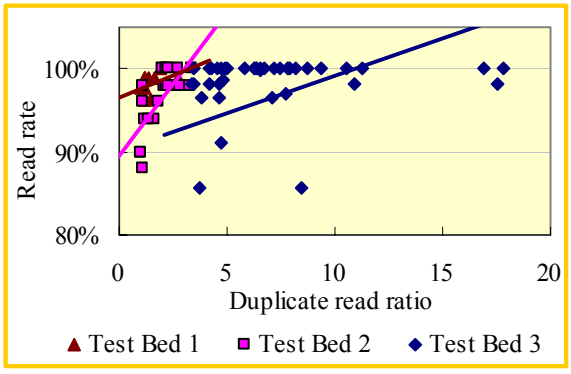

Figure 5. Pairwise scatter plot of duplicate read ratio and read rate

Another interesting observation from Fig. 5 above is the slope of the fitted line for Test bed 2 is steeper than that of Test beds 1 and 2. If slopes for each test

bed are thought of as the strength of the relationship between duplicate read ratio and read rate, the steeper slope says the read rates in Test bed 2 were more sensitive to the reader's RF power. In fact, only Test bed 2 tried those tags with a shorter read range, while the other test beds were dedicated to the other type of tags. Thus, with a small change to RF power, shorter range tags would end up with a rather large gain or loss in the number of tags read. Admittedly, this does not convey any statistical significance for the same reason stated earlier.

The variability of read rates in Test bed 3 has lent itself to further analysis, but the sample that arose from Test bed 3 is not totally random. The read rate of one pass is dependent on the outcome of the previous pass to some degree, because of a consistent effort to increase read rate by selectively changing some of the previous parameter values. Thus, 38 passes from Test bed 3 were re-organized into groups that have the similar values for some test parameters, as shown in Table 5 (several passes did not fall into any of the groups). Moving from group I to V, the mean read rate tends to increase while the variance of read rate is decreasing (see also Fig. 6). This observation suggests that under the set of field conditions classifying trips into group IV or V, the technology under consideration is most likely to achieve 100% reading of 56 tags every time the load of pipe spools is shipped/received through the portal.

The question is whether the field test data supports

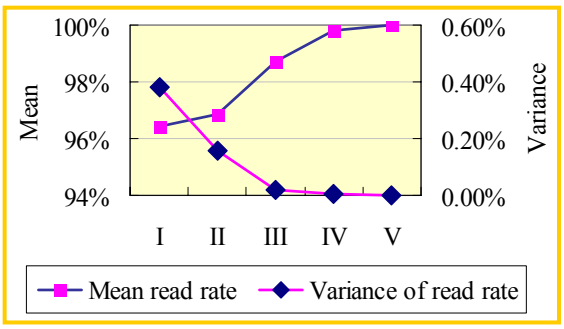

Figure 6. Mean and variance of read rates

the assertion that the differences of the mean read rates between groups of trips are statistically significant. This question is answered by means of statistical hypothesis tests on the differences in mean read rates between comparable groups; 1) groups I and IV, 2) groups II and IV, and 3) groups II and III. Statistical hypothesis testing usually requires some test statistic to define a rejection region from the sample space where the null hypothesis (H_0) is rejected and hence the alternative hypothesis (H_1) accepted. Now we derive a test statistic.

Let p_i denote the probability that each tag will be read (i.e., the read rate) during passes of Group i, and each tag is assumed to have the same p_i in every pass under the field conditions characterized by Group i. Then the number of tags of the total 56 that are read in each pass of Group i, Y_i has a binomial distribution with parameters 56 and unknown p_i, or $Y_i \sim \text{Bin}[56, p_i]$. Further, let n_i denote a sample size of Group i (i.e., the number of trials or trips, e.g., $n_1 = n_4 = 9$), and Y_{ij} the number of tags read in jth pass of Group i. Then observed values of Y_{i1}, Y_{i2}, ... , Y_{ini} would have yielded a random sample of size n_i since 1) they arise from the identical binomial distribution and 2) every Y_{ij} is independent of one another provided that the underlying dependency between successive trials has been addressed by the reconstruction of the overall sample. Y_{ij} can then be added up to represent the number of tags read for Group i as a whole, without loss of randomness, and approximated to a continuous Normal random variable:

$$\sum Y_{ij} \sim \text{Bin}[56n_i, p_i] \approx \text{N}[56n_ip_i, 56n_ip_i(1-p_i)] \sim Z_i \quad (1)$$

Manipulating (1) gives us another random variable $Z_i/(56n_i) \approx \text{N}[p_i, p_i(1-p_i)/(56n_i)]$, which represents the read rate for Group i (note its mean is p_i). Finally, the statistic Z_{ij} given by standardizing $Z_i/(56n_i) - Z_i/(56n_j)$ is used to test the null hypothesis H_0: $p_i = p_j$ (no difference in mean read rates between Groups i and j) against H_1: $p_i < p_j$. Table 6 shows there is a statistically significant difference between Groups I

Table 5. Test Bed 3 Decomposed into Groups of Trips

Group no.	No. of trips	Reader on/off timing (before/after trailer front/rear end)	Travel speed	No. of antennas; traveling direction	Mean read rate	Variance of read rates
I	9	5~6 m; 6~7 m	1 mph	2; counter-clockwise	96.4%	0.383%
II	4	5 m; 3~9 m	5 mph	4; counter-clockwise	96.9%	0.157%
III	7	0 m; 2 m	4~5 mph	4; either direction	98.7%	0.018%
IV	9	5~6 m; 6~7 m	1 mph	4; counter-clockwise	99.8%	0.004%
V	6	0 m; 0~1 m	2 mph	4; clockwise	100.0%	0.000%

Table 6. Hypothesis Test Result for Groups I and IV

Group no.	No. of trips	Reader on/off timing	Travel speed	No. of antennas; traveling direction	Mean read rate	Z_{14}	$Z_{0.01}$
I	9	5~6 m; 6~7 m	1 mph	2; counter-clockwise	96.4%	-3.968 <	-2.326
IV	9	5~6 m; 6~7 m	1 mph	4; counter-clockwise	99.8%	Reject H_0	

and IV (at significance level α=.01). The results for other groups are in Tables 7 and 8. The results of hypothesis tests showed that the number of antennas enabled and the truck traveling speed have a significant impact on the read rate and that the read activation duration does have some effect on the read rate, but not as significantly.

Table 7. Hypothesis Test Result for Groups II and IV

Group no.	No. of trips	Travel speed	Mean read rate	Z_{24} $Z_{0.01}$
II	4	5 mph	96.9%	-2.482 < -2.326
IV	9	1 mph	99.8%	Reject H_0

Table 8. Hypothesis Test Result for Groups II and III

Group no.	No. of trips	Reader on/off	Mean read rate	Z_{23} vs. $Z_{0.05}$
II	4	5 m; 3~9 m	96.9%	-1.430 > -1.645
III	7	0 m; 2 m	98.7%	Accept H_0

However, it should be noted that the small sample size n_i restricts the credibility of the statistical hypothesis tests. For optimal credibility, samples of size larger than 100 would have been required of our normal approximation to the binomial distribution of $Z_i/(56n_i)$ so that $p_i \pm 2\sqrt{p_i(1-p_i)/(56\,n_i)}$ can lie in the interval (0, 1) [10].

5. CONCLUSIONS

To assess the technical feasibility of RFID technology in the construction industry, the field tests have been conducted as part of the FIATECH Smart Chips project. The field trials were primarily concerned with such applications that would improve efficiency in manual receiving and inventory of fabricated pipe spools in laydown yards and automatically track the shipments at major portals located in the supply chain.

Phase I field tests have addressed many technical issues related to the envisioned applications, and the results indicated that current active RFID technology could function effectively in the construction field environment involving large metal objects and requiring relatively long read range. Furthermore, Phase II field trials tested the reliability of the technology in the portal application to automatically identify pipe spools in typical transportation conditions, and the results showed with limited credibility that the current technology can achieve 100% accuracy and precision under a certain set of field conditions which can be accommodated by the potential users.

In addition to the technical feasibility of RFID technology, potential economic benefits should also be assessed before implementation of the envisioned applications. The authors have identified several promising areas in the current work process, and are currently assessing the overall economic benefits possible by implementing the applications of RFID technology.

Acknowledgement

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AN APPLICATION OF AUTO-IDENTIFICATION SYSTEM IN STEEL STRUCTURAL CONSTRUCTION PROCESS

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Abstract: Being an integral part of accessing the modern automated system, Auto-ID (Automatic Identification) system is a proven technology of providing a more accurate, detailed, timely and advanced information for architectural operation. Currently, the various technologies that are used for Auto-ID are: barcodes, optical character recognition (OCR), radio frequency identification (RFID), magnetic stripe and voice recognition. The focus of this study is mainly on the interface integration of Auto-ID system, including barcode, radio frequency, wireless technology and database systems etc. Among the diversified expert fields in the construction industry, the methodologies used for site-casting and pre-casting steel structure are very similar to that of manufacturing industry. By setting up suitable Auto-ID system module for construction environment and taking actual steel structure construction case as an example, a preliminary prototype has been developed in this study. After the prototype is thoroughly analyzed, guidelines that aim at effectively initiate the utilization of this Auto-ID system is formulated and ideas for further research are recommended.

Keywords: Aut-ID, Bar Code, and Steel Structural Construction Process

1 INTRODUCTION

This study focuses on interface integration of bar code system, including the bar code system, wireless technology and database system etc., so as to set an Auto-ID system module for construction environment. Furthermore, a practical steel structure construction is established as a case study herein to propose a primary module for Auto-ID system.

Within the various fields of construction industry, steel structural engineering is very similar to manufacturing industry in terms of its material and manufacturing processes, as well as manufacturing application, indicating that Auto-ID system can also be applied in the practical operation of steel structural engineering. While Bar Code Auto-ID system has already been collaborated with the function of Data Base sytem, and together with the wireless transmission of information, the application of this mechanism to steel structural engineering should be very feasible.

2 SYSTEM ARCHITECTURAL DESIGN AND ANALYSIS

Auto-ID system can be directed into various procedures of construction material and production processes, such as production planning, product design, manufacturing, material transportation, on-site storage and installation etc., [1] so as to reach the purposes of installation consistency and standardization, paperless and unmanned conditions, and also considerably reduces human data entry errors and time required. Subsequently, it is hoped that both the productivity and economic efficiency of the construction can be improved. Based on this concept, this paper suggested that project such as "high-raise story steel structural building," which requires repetitive construction methods and consistent steel parts, is very suitable in incorporating with Bar Code Auto-ID System. The life cycle of steel structure building project can be viewed as an integrative process. Based on its operational characteristics and special requirement, appropriate concept of Bar Code ID system is adopted and applied to the most feasible scope in times of the building construction. Figure 1. indicates a preliminary simulative system that is established herein for meeting the requirement of engineering automation. The so-called life cycle of steel structural building projects covers the areas of steel structural planning, structural part design, manufacturing and storage, transportation and erection of parts, and on-site temporary storage. Also, this concerns the total processes of practical erection and installation, including the treatment of fundamental parts such as column and beams as an object, whereas the dimension, weight, steel type, connection method, placement in the building, storage area, transportation sequence and erection order etc. of its similar columns and beams are all treated as behavioral objects. By so doing, the behavioral parts having the same nature can be inherited and attributed completely. Through the “Read” function of Bar Code Identification, full

automation can be achieved towards the OODBS (Object Oriented Data Base), which is a type of data base management module that has widely been promoted in IT industry within the past few years.

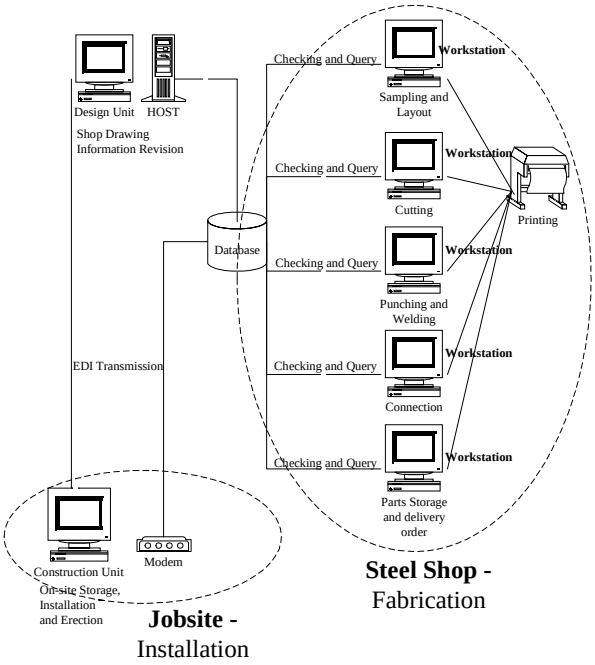

Fig 1. A Preliminary Simulative System for Steel Construction Work Flow

2.1 Workflow of Steel Structural Engineering

The above section illustrates a brief workflow adopted in traditional steel structural engineering. It is expected that by implementing a better data processing method, its overall efficiency can be optimized. Table 1 demonstrates the critical management items and Auto-ID design requirement for a typical steel structural building.

(1) Design and Planning Stage (Pre-production Stage): In this stage, an integrative coding process can be accomplished based on the design materials, such as guideline and drawings etc., of the columns and beams. Coding every part is very necessary in building the bar code system, in which the attributes of the parts, such as dimension, weight, steel type, connection method, placement different story of the columns and beams have to be considered, built and saved in the Data Base System.

(2) Factory Manufacturing Stage: In this stage, through various mechanisms that are established in the design planning stage, namely, data base submittal and document, shop drawing files and computing technology such as Intranet and Internet configured within an organization, documents and information of the engineering can be digitalized for real time enquiry and mutual transmission. By so doing, manual processing can be greatly reduced, while increasing the transmission speed, and maintaining the accuracy of the recorded information. Upon completion of manufacturing the parts, bar code identification towards the coding of parts, which has been the outcome of the previous step, is immediately executed. Respective bar code is labeled on the areas of parts which are more visible and not easy to wear off. At present, iron or copper-casted bar codes are available for job site where the parts are prone to wear and tear.

(3) On-site Erection Stage: By means of bar code and Auto-ID function, problems of partitioning and stacking order, such as parts transportation (i.e., transporting the parts from the factory to job site in the right stacking order), on-site temporary storage, and erection etc. can be solved, so as to considerably reduce manual identification time and human identification errors, prevent labor and machinery idling and subsequently lead to the increase of production and economic efficiency.

Table 1. Critical Management Items and Auto-ID Design Requirement of Steel Structural Building

Procedure	Item	Requirement	Automation Requirement
Production	Assessment of design drawing standard	Queries and clarification of errors and inconsistency	Establishment of coding system
	Writing and editing of construction planning proposal and drawings	Meeting the quality requirement of design/supervise-ory units	Establishment of data base system
Preparation			Establishment of document and graphic folders Establishment of EDI[1]
Factory	Material in-factory management	Meeting the quality requirement	EDI feedback transmission
	Welding process	Meeting the requirement of construction process proposal	Convert the coding into bar code Auto-ID system
Manufacturing	Dimensional precision of the completed parts	Proper usage of processing and assembling equipment	

[1] EDI: Electronic Data Interchange

On-site	Bolt anchoring process	Meeting the requirement of construction process proposal.	Auto-ID system operation and storage
	Precision of erection and assembling	Meeting the requirement of construction process proposal.	Erection and installation of Auto-ID system
Erection	On-site welding process	Meeting the requirement of construction process proposal.	Checking and recording feedback

2.2 Establishing the Data Base System

Viewing parts as objects, categorize those sharing the same attributes, such as size and weight etc., into the same group. Next, analyze into the structural information (such as storage area of the parts, layers and production sequencing) and then plan for the construction process accordingly.

2.3 Establishment of a Search Hub-Basic Concept

Based on the design standard and detailed drawing of the construction, search hubs are established at the major stations controlling and tracking the engineering process by means of bar code. Also, with appropriate setting of checklist, it is possible to examine whether the quality of every part can comply with the ideal design standard and drawing. As a result, quality inspection can be undergone before every part leaves the factory.

3 BENEFITS OF ADOPTING AUTO-ID IN STEEL STRUCTURAL ENGINEERING

3.1 No Need to Identify the Steel Parts by Manual Labor

Traditionally, when steel parts are produced and ready for shipment, they are painted with dominant marks, showing their on-site placement position such as North, South, East, West (or A, B, C and D), as well as other information such as serial number, weight, and numbers of sections etc., so as to optimize the storage process. However, if Bar Code System is adopted and the prepared bar codes (which can be produced by either iron casting or plating confronting the wear and tear problem in the job site,) are labeled on them before leaving the factory, their identity can then be read directly by a portable decoder. Subsequently, manual labor can vastly be saved, and possible errors in identifying the parts can be reduced [2].

3.2 No Need to Produce Huge Quantities of Forms and Documents

Traditionally, before the steel structural parts are sent to the job site, manufacturer has to prepare complete processing and quality control documents of their products (such as quality control chart, inspection chart, process control sheet and checklist etc.), so that the site workers would fully understand the specification of these parts [3]. When the parts have reached the on-site temporary storage area, operators still need to undergo paper works for an effective erection procedure. However, if bar code system is implemented, manufacturers can use EDI to maintain the quality control documents, and acquire basic information of the parts, such as size, weight, serial number, numbers of sections and storage area etc. They can then transmit these data to the site operators, preventing them from repetitive data entry. Instead, they are required to identify the parts with bar code, and then extract related information from the database. This method can improve the job performance and accuracy of the total process.

3.3 Enhance Productivity

Another selling point of automation is the improvement of productivity. With today's labor shortage and labor and material cost increase, automation is an unavoidable trend in all sorts of industries, ensuring industrial upgrade and increase competitiveness in the international scene. Introduction of bar code Auto-ID system and EDI into construction industry are exactly the means to leverage the potential of automation.

4 SYSTEM HARDWARE AND SOFTWARE

4.1 System Hardware Structure

This system comprises of bar code automatic identification and wireless data transmission functions. In this section, the hardware system configured in the research thesis is introduced, wherein the main devices are all provided by Intermec Company [4 & 5], including the construction use bar code scanner, construction use portable wireless transceiver and construction use wireless digital adapter, as well as special hardware devices such as construction use wireless digital network controller etc. All these devices perform the functions of data entry, decode, transmission, control interface, and storage etc. Detailed description of these system devices is as follows.

Figure 2 shows the system hardware structure, wherein the processing of this set of hardware devices starts at Intermec 9465, the data collector.

This collector receives data from the on-site bar code, which then transmits data by means of spread-spectrum wireless frequency. Also, it receives data acquired by bar code via Intermec 9181 main data transceiver, and then send it back to host computer for further processing [6].

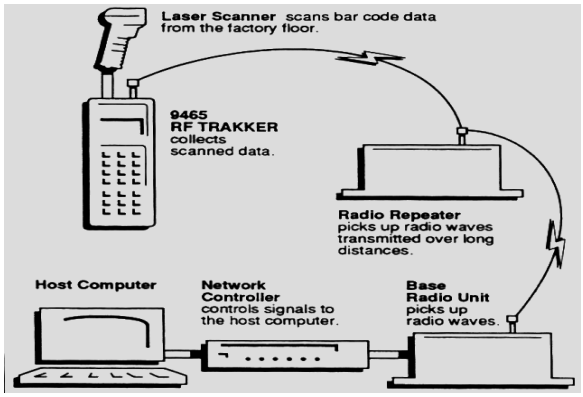

Figure 2. System Hardware Structure

4.2 Bar Code Laser Scanner

As shown in Figure 3, the Bar Code Laser Scanner is developed by Intermec Company, having the product serial number of KB1565A01 (or simply 1565). This scanner scans bar code directly by means of laser visible, and then immediately displays the decoded bar code on its digital monitor (Vacuum Fluorescent Display having 4 lines of 20 characters). Its accessory of a small keypad carries multiple scanning functions, including scanner, display and keypad. Also, this scanner can decode bar code of different format and mode (including UPC/EAN, Code 39, Codabar, 2 of 5, Code 11, Code 93, Code 128 and UCC128.)

Figure 3. Bar Code Laser Scanner

Portable Wireless Transceiver, product serial number being 9465A02010 (or simply 9465), is also known as Collector in Real-time developed by Intermec Company. This RF Transceiver can transmit two-way interactive data through spread-spectrum radio frequency, allowing both manual data entry (keyboard containing 48 keys) and connected bar code scanner (1565) data transmission. Its internal is interpreted and edited by Interactive Reader Language (IRL), which is also developed by Intermec Company, providing program designer the necessary tools for program development and utilization.

Developed by Intermec Company, Wireless Digital Network Controller is also known as Network Controller, and its product serial number is KB9180 (or simply 9180). As shown in Figure 4, this device mainly supports the wireless transceiver and the network control of wireless digital adapter, which is used for connecting Host Computer, processing the asynchronous communication. It can also support data transmission to 128 sets of wireless transceiver (9465) at the same time.

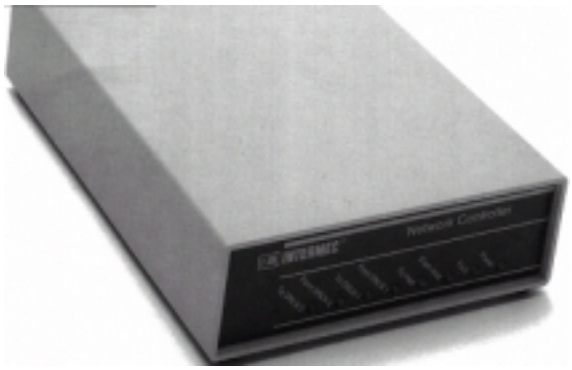

Figure 4. Wireless Digital Network Controller -Network Transceiver

4.2 System Software

The system software includes: document processing software of Microsoft Word, graphics treatment software of VISIO 5.0, IRL bar code interpretation and editing programming language which is developed by Intermec Company, and Intrscan operation environment system software. Also, the bar code labeling and editing software of LBCC 2.5 is adopted. All these software are performed under the operation system of FOXPRO for Windows carrying multimedia data base function.

This system selects Microsoft Windows Chinese Version to be the operation environment of the system. The main reasons being: Windows carries the properties of “object-oriented” as well as the functions such as DLL (Dynamic Link Library), OLE (Object Linking And Embedding) and DDE(Dynamic Data Exchange) etc., so that the applications being executed under Windows can easily deliver and exchange data between each other without the limitation of 640K memory. Besides, some unique functions such as GUI (Graphical User Interface), DIG (Device Independent Graphics), Device Independent Graphics and MDI (Multiple Document Interface) have enabled Windows to be the best PC's operation environment to develop and

create multi-media system.

5 INPUT, OUTPUT AND FUNCTION DESIGN OF THE SYSTEM SCREEN

The major function of the system is to provide users with detailed content search of the steel parts. Through the multi-functional data base screen builder of FOXPRO 4GL, the configuration of the system screen is as simple as to place different interface objects on the displayed panel, so as to build the graphics style, as well as the complicate data entry screen format. The screen designed by the system is used to describe the integration of Auto-ID system. Together with wireless technology and the fourth generation data base languages, it is applied on the primary module constructed by the steel structural construction engineering.

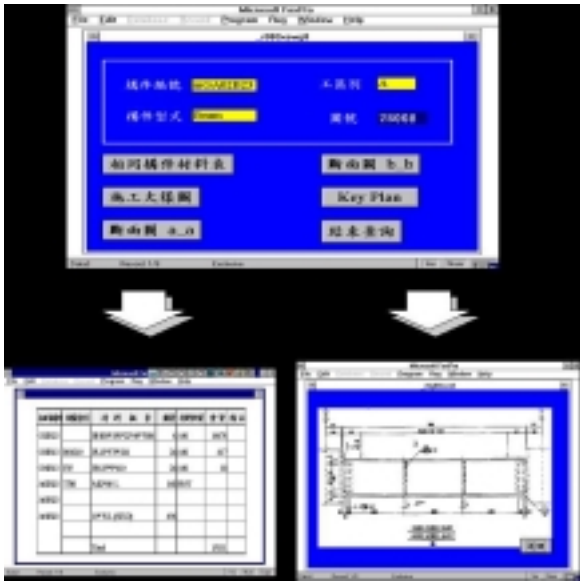

Figure 5. Screen Desing-1

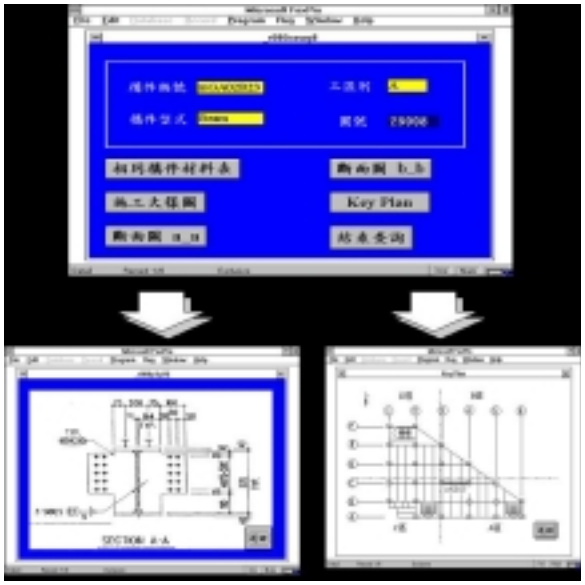

Figure 6. Screen Desing-2

5 CONCLUSIONS

The following findings can be drawn as the conclusion of this application:

(1) Integration of Auto-ID system can greatly improve productivity.
The ultimate purpose of single data base concept is to achieve the automation of integrative engineering, wherein Auto-ID system is indispensable in its configuration. From the information collected in this research, it is known that with the collaboration of other technology, such as EDI, CAD, Robot, Expert System and Multi-media etc., it can greatly improve the productivity of construction.

(2) Collaboration of Auto-ID System based on the characteristics of construction industry.
Because of its complicate and changeable characteristics, construction industry varies greatly from most commercial and industrial business. As a result, successful commercial, industrial or other business-related case studies may not be fully applicable to this specific area. Emphasis should be placed on analyzing and assessing its unique nature, so as to optimize the processing performance.

(3) Cost efficiency of whole system should be fully considered.
Nowadays, Auto-ID system is a very sophisticated technology, which is vastly applied in different scopes, such as material management, tracking of labor affairs, financing and equipment management and document control etc. However, upon considering the adoption of this new technology, decision makers always consider the incurred cost while overlooking the performance that this technology can bring forth. For example, Auto-ID system can provide real time, historical and comparative processing, enabling a quick and accurate decision-making. Currently, popular known as RFID can serve either as AUTO-ID or auto data collection system. Regardless of its role, the new system should collaborate with management tools that are commonly used in construction industry (such as budget estimation, construction status control, cost control, performance evaluation, and S-Curve etc.), so as to achieve its management functions. The issue of integrating these technologies and management tools should be set as the research direction in the future.

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SYNCHRONOUS CHAT FOR KNOWLEDGE SHARING IN A DISTRIBUTED DESIGN ENVIRONMENT

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Abstract: The knowledge of design experts, mostly tacit, holds tremendous value if made reusable for the right project at the right time. With emerging CMC (Computer-Mediated Communication) technologies, architectural practice has been transformed and faces new opportunities for capturing and reusing tacit design knowledge in a distributed design environment. This paper describes the impact of tacit design knowledge shared and captured by using online, interactive chat-based software. DKM (Dynamic Knowledge Map) has been developed to employ synchronous CMC to assist in the reuse of design experts' tacit knowledge in a distributed design environment. The software was tested it in a distributed design environment involving a high degree of expertise and consequent need for applying tacit knowledge. An instrumental case study approach was used for this research. Data were collected and analyzed using both qualitative and quantitative methods to enhance the validity of findings: content analysis, log files, simple statistics, and questionnaires. The results indicate that the interactive chat sessions and archives positively influenced the students' design performance by means of tacit knowledge sharing. This research also suggests that the importance of tacit design knowledge may be confidently enhanced through careful design in a distributed design environment.

Keywords: tacit design knowledge, Computer-Mediated Communication, Synchronous Chat, Knowledge Mapping

1. INTRODUCTION

Tacit knowledge is unwritten knowledge, such as expertise or professional insight, which is formed as a result of experience. Throughout the life-cycle of a project, architectural professionals rely heavily on their tacit knowledge for complicated design decisions [1]. For example, novice practitioners gain tacit knowledge through either direct experience or receiving instructions, and begin to extend the web of knowledge in the architectural domain. The tacit knowledge of architects has tremendous value if combined into one body of knowledge and shared with the right people at the right time.

Current architectural design process has been described as a multi-participatory distributed design environment [2]. With emerging Computer-Mediated Communication (CMC) technologies, architectural practice has been transformed and faces new opportunities for capturing and reusing tacit design knowledge in a distributed design environment. However, tacit knowledge sharing, although acknowledged as important to AEC firms, has not been confidently implemented through CMC. There are no accepted CMC strategies for managing tacit knowledge in the AEC industry. Therefore, there is a need for empirical research to fully exploit the potential of CMC technologies and enrich understanding of reusing experts' tacit knowledge in a distributed design environment.

This paper describes the impact of tacit design knowledge shared and captured by using online, interactive chat-based software. DKM (Dynamic Knowledge Map) has been developed to facilitate synchronous chat for assisting in the reuse of design experts' tacit knowledge in a distributed design environment. The software was tested in a distributed design environment involving a high degree of expertise and consequent need for applying tacit knowledge. Although statistical analyses have not been undertaken, quantitative and qualitative observations of the software use provided valid evidence to guide the direction of an appropriate use of tacit knowledge for architectural practitioners.

2. RELEVANT RESEARCH

Reviewing literature on knowledge sharing in a design studio [1], and Computer-Mediated Communication [2] elaborates the theoretical foundations and provide some preliminary answers to these unexploited questions: How can CMC assist in capturing and sharing experts' tacit knowledge? What are the problems associated with the integration of CMC into a distributed design environment?

A major limitation of current design studies is that little research has examined the potential of CMC to support the reuse of tacit design knowledge in a distributed design environment. In the field of CMC research, a few articles [3,4] report several key

findings where online chat or instant messaging systems successfully support tacit knowledge sharing in a typical business environment. They also argue that CMC could improve the access to tacit knowledge and might offer an organization a competitive advantage by improving its efficiency and expertise.

Several researchers in the field of architecture have emphasized the importance of tacit knowledge sharing in architectural design environments. For example, Schon [1] convincingly demonstrated that experts' tacit knowledge is a very important resource in the architectural profession. He explored the traditions of the architectural studio to investigate how architectural students learn from instructors in a design studio, insisting that design knowledge can be shared by reflective conversations within a design situation. Suwa et al. [5] stressed the importance of tacit knowledge in the design profession, especially in an educational sense. Cross and Cross [6] also conclude that the knowledge sharing process of design significantly influences the quality of design.

In the domain of architectural research, very few design research have been conducted concerning the effects of Computer-Mediated Communication on the architectural profession. Huang [2] studied the implications of collaborative media on design process by employing organizational economics theories. Kvan and Candy [7] conducted experiments to investigate the role of the computer system on the collaborative design communication over computer networks. In this study, chat-based software played a significant role in producing better design communications. However, their research did not explore the impact on the design artifact of reusing tacit design knowledge; rather, they focus on facilitating design communication.

3. RESEARCH QUESTIONS

The long-term goal of this research is to establish a theoretical foundation for clarifying the contribution of experts' tacit knowledge in the AEC industry and improving the documentation, access and reuse of tacit knowledge in distributed design organizations. The specific objectives and corresponding research questions of this research are to:

1) Observe the effect of tacit knowledge sharing, utilizing DKM, on the students' design artifacts.

   Research Question 1: How can DKM assist in capturing and sharing tacit design knowledge?

   Evidence

   - Working software that implements the proposed theory.
   - Opinion of software adequacy, collected through a questionnaire and students' feedback.

2) Do students who share tacit knowledge through synchronous chat apply the knowledge on their design artifacts?

Evidence

- Content analysis of dialogue transcripts, recorded through chat sessions.
- Analysis and criticism of design artifacts carrying the effects of tacit knowledge sharing.

4. METHODS

4.1. Research Design

An instrumental case study [8] approach was used in this research. Stake emphasizes the importance of multiple data sources in order to provide multiple perspectives. Data were collected and analyzed using both qualitative and quantitative methods to enhance the validity of findings: content analysis, log files, simple statistics, and questionnaires.

The focus of observation for this research is "tacit knowledge sharing operated by DKM in a design studio" as illustrated in Figure 1.

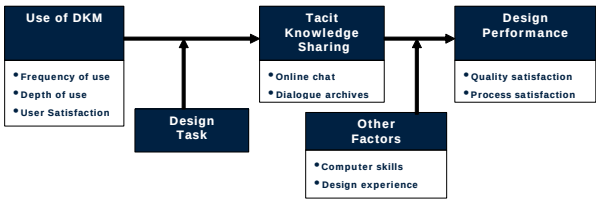


Figure 1. The Focus of Observation

4.2. Context

A graduate-level design studio at a southern university was selected; the studio conducted a design project on the long- term planning and design of facilities at the Peckerwood Garden in Hempstead, Texas. Three faculty members in the College of Architecture organized the design studio for graduate students from the Architecture, Landscape Architecture and Construction Science Departments.

DKM was introduced and integrated with traditional face-to-face design critiques, and all activities on DKM were tracked using log files. The computers used for the chat sessions are located at the university computer lab a setting that offers the same quality of using personal computers. The lab is very convenient to use and it is impossible to change any computer configurations or network settings.

4.3. Participants

Twelve graduate students, enrolled in an architectural

design studio at the university, were selected for this study. The participation of the research was voluntary and was unrelated to their class grade. The participants' average age was 21 years. They had one to two years of architectural design experience and all had previous experience on the same type of project. Twelve knowledgeable design experts, such as faculty members and architects who are technologically experienced, were selected and invited to be reviewers. They shared their tacit knowledge with students for the project by actively communicating using DKM. The researcher did not participate in chat sessions, except to answer technical questions and to help with software use.

4.4. DKM

DKM demonstrates new methods of sharing tacit design knowledge that include locating, selecting, and communicating with other architects who experienced a similar project. It is a synchronous CMC system with some functionality of asynchronous CMC added. The major functionality includes chat room, chat archive and expert search. The user of DKM searches for experts and facilitates communication with the experts. One of the major functionality provisions is to support the synchronous chat of design experts for sharing and reusing knowledge (See Figure 2).

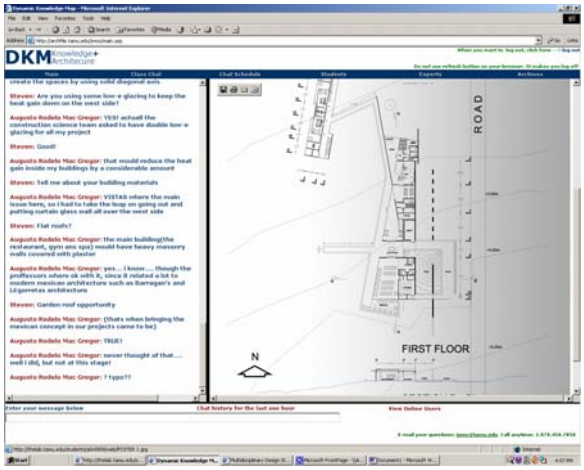


Figure 2. Screen shot of DKM

Architects shared their tacit knowledge by actively communicating with students using DKM. All dialogues were saved in a database as records of tacit knowledge sharing, and made accessible for non-participants to retrieve them for sharing the tacit knowledge conveyed in the dialogue. DKM incorporates a database for managing a chat archive to enable a knowledge seeker to gain advice from an expert. In addition, a grading function enables the system to develop a measure of usefulness or reliability of individual expertise on various design topics.

4.5. Data Collection

Two qualitative data were used for the content analysis: online chat transcripts and students' design artifacts. The online chat transcripts comprise messages between design professionals and groups of students. The actual chat content is analyzed to figure out how synchronous communication is used in a distributed design environment. The students' design artifacts comprise drawings and presentations that are produced in the design studio. Students' design artifacts were investigated to discover the improvement as a result of online chat conversations. Quantitative data mainly supplemented qualitative observational data to triangulate evidence to produce valid conclusions. Two questionnaires were distributed to the participating students to collect quantitative data. The online student questionnaire consisted of two pages, four of which were Likert type and semantic differential scale check boxes. Survey web location was sent by email message before couple of weeks before the last week of the semester.

The first survey was conducted on the first day of the experiment and collected the descriptive data about students' attitude of gathering design knowledge, previous design experience, tacit knowledge utilization and the use of CMC. The second survey was conducted on the last day of the design studio. This questionnaire is primarily designed to get feedback about software usability, ideas and satisfaction.

The numerical data about actual usage of DKM was collected by the log files of the database system embedded in DKM. These log files effectively recorded every action that every user performed within DKM, including logging in and out; creating, joining, and leaving dialogs; reading chat archives.

4.6. Data Analysis

Analysis of the chat transcript consisted of an iterative search for patterns that were meaningful to the design projects. The first step of content analysis began with reading the chat transcripts to investigate what people discussed in the chat sessions. Then, a code scheme were devised from themes emerged with repeated reading and past literature about theories of knowledge management and design studies. The entire messages in the chat transcripts were analyzed sentence-by-sentence and divided into small units by using three dimensions of categories; knowledge types, design activities and communication behaviors as shown at Figure 3. Gero and McNeill [9]'s coding scheme of design activities has been adopted as an initial reference in obtaining the major categorization of the chat messages in this study. Then, the coding scheme were extended and adjusted to cover the chat messages effectively.

Knowledge Type	Design Activities
Tacit Knowledge	Analyzing Problem
Explicit Knowledge	Proposing Solution
MISC.	Analyzing Solution
	Explicit Strategies

Figure 3. Coding Scheme

With this coding scheme, students' design artifacts were analyzed to discover the occurrences of tacit knowledge reuse and identified their role in students' design artifacts. This process will be qualitative and emergent to observe new phenomena freely [10]. However, the code scheme will let to answer following questions in a systematic way; what types of knowledge have been used to improve design artifacts? What kinds of design processes have been improved by using tacit knowledge? What aspects of design quality have been improved by using tacit knowledge?

5. FINDINGS

5.1. The role of DKM in tacit knowledge sharing

The analysis of log files and questionnaires is described in this chapter in order to answer the first research question, *"how DKM can assist in capturing and sharing experts' tacit knowledge?"* All students participated in the design studio completed and submitted a pre-experiment questionnaire. 7 students out of 12 students were involved in the chat sessions while 12 design reviewers logged in to the system for the chat sessions. They logged in at least three times, and stayed at least one hour, and produced at least 50 messages. 7 chat sessions were conducted during one month experimental period. Each chat session lasts approximately one hour. The participants produced 1,162 messages.

5.2. User Satisfaction

The data from questionnaires were used to evaluate the software and to consider how the software could be improved and implemented in a distributed design environment. Table 1 shows students' answers of their satisfactions on DKM. Significance statistics are not reported for the data due to the small sample size.

Overall, all students reported that they would consider using the software for sharing design knowledge in their next design studio. Student perceptions of chat were very positive. On a scale of 'Frustrating' to 'Very enjoyable', All students claimed favorable ratings. Most of them reported that their experience with the software was very enjoyable and the software is well-designed to support sharing of design knowledge (See table 1). Students expressed that chat sessions were rated very enjoyable. Although some basic user interface issues had not yet been resolved (for example, screens are continuously refreshed so that chat thread cannot be read.). However, these data indicate that participants were very satisfied with the functionality of the software in terms of knowledge sharing. All respondents said that they would use this software in the next design studio.

Overall, how would you describe your experience on the software?								
Very enjoyable	2	2	2	0	0	0	0	Very frustrating
How would you describe your experience on the chat sessions?								
Very enjoyable	2	2	2	0	0	0	0	Very frustrating
How would you describe your experience on the chat archives?								
Very enjoyable	0	1	1	4	0	0	0	Very frustrating
Overall, is the software well-designed to support sharing of design knowledge?								
Strongly Agree	0	4	2	0	0	0	0	Not at all
Overall, do you think that the software is useful to improve your design project?								
Strongly Agree	1	2	3	0	0	0	0	Not at all

Table 1. Answers from the post-experiment questionnaire

5.3. The Impact on the Design Artifacts

The analysis of chat transcripts and design artifacts is described in this chapter in order to answer the first research question, *"Do students who share tacit knowledge through synchronous chat and apply the knowledge on their design artifacts?"* All chat messages were categorized by using the coding scheme mentioned in the above chapter. Table 1 shows the number of chat messages produced by the participants using the coding scheme. Figure 4 shows examples of chat messages of each category.

Message Category	MISC	Explicit Knowledge	Tacit Knowledge
Proposing Solution	19	10	79
Analyzing Solution	5	14	72
Analyzing Problem	17	5	13
Explicit Strategy	28	90	9
Non-design	414	12	11
Total	483	131	184

Table 2. Number of messages by each category.

Design artifacts and chat transcripts were analyzed to learn how the students apply the knowledge discussed in the chat sessions. During the chat sessions, the reviewers identified problems on the spacing of the building (See Figure 5). The reviewers' comments formed the most concrete

evidence of the problem. Quickly, the student identified particular problems that would influence their approach to developing a final design. A student produced a floor plan which is improved by the comments from the virtual reviewers, as shown in Figure 5.

Knowledge Type	Example
Tacit Knowledge	• It also helps me to create the spaces by using solid diagonal axis. • And keep in mind, that you can improve environmental friendliness one component at a time. Some things the owners demand, other things you can propose. Even green buildings are not ALL green.
Explicit Knowledge	• Is "Natural Capitalism" required reading there yet?
Other	• On slide 3, you may see the bigger first floor plan. • The walls are framing each space of my Meeting center.

Figure 4. Examples of chat messages

5.4. Comments from the participants

We also analyzed some responses from open-ended questions. Students were asked to make comments and recommendations about what should be improved in the software for more comprehensive design knowledge communications. These students' comments are valuable for improving the quality of DKM because these responses identify some weakness of current software. Students report some user interface problems and ideas that could be better in next time. The students' responses to this question included:

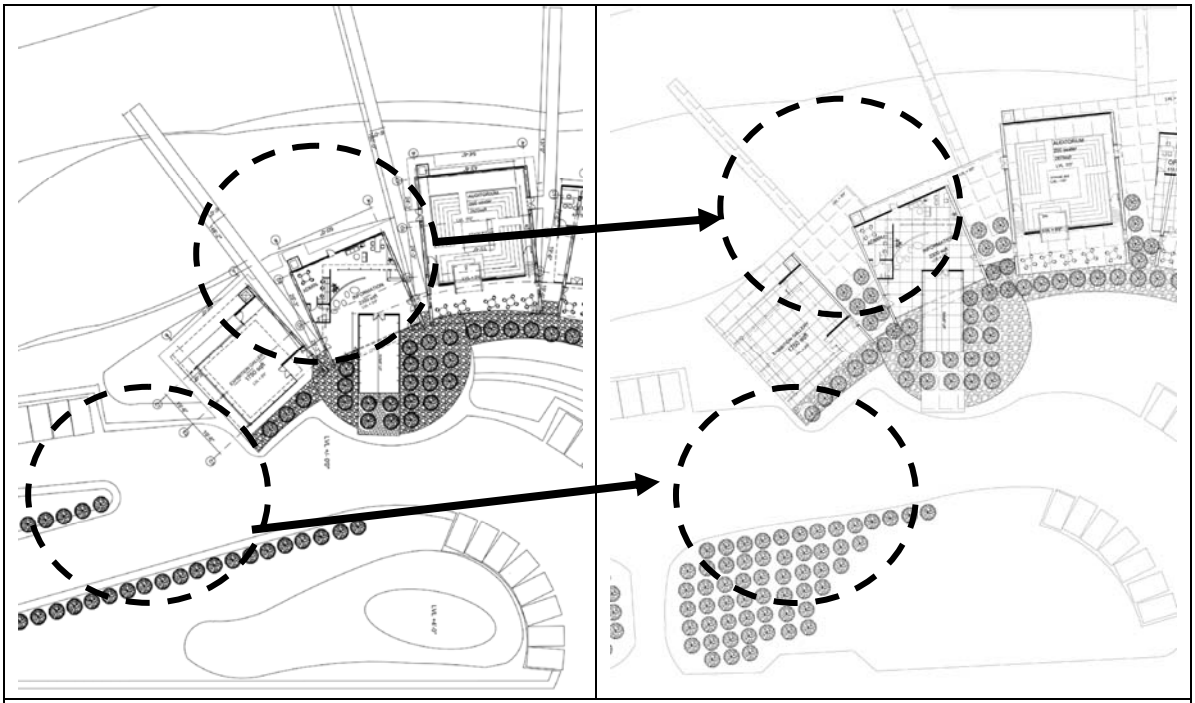
"I feel if the fact that the page is being refreshed continuously makes it difficult to read the chat conversation already taken place, although you have provided for the history option."

"If you could some how fix that I think it would be great. Also I know your intensions are different but if some sort of markup system could be provided it would be perfect. As architects always tend to draw...that's all the suggestions I have."

"Experts need access to the history of the project such as who is the client, what are the goals, what skills or knowledge do the various students (or agents) bring to the project."

"Reviewers need to spend more time to catch the online discussion."

Comments are of the reviewer taken from emails. All reviewers were very positive about the potential



Reviewer 1: I feel that maybe the center of the arch needs to be referenced / celebrated....I mean the point across the parking
Reviewer 2: Your boxes are always open in one way or another.... therefore the edge of the walls are going to be VERY important....what is the material relationship between the face of the walls and the edge of the walls...color...material...
Reviewer 3: what is the spacing between buildings?
Reviewer 4: spacing at the narrowest point - that is closest to parking is too narrow..
Reviewer 5: maybe a big tree.... the Landscape Architects may like that....

Figure 5. An Example of a building design improved by the chat session

impact of the software in terms of its ability to share design knowledge. Several reviewers pointed out that participation would have been greater and the measurable contribution could have been much greater, if the design project had begun using this interface in the earlier stage. The maturity of the project discussed in the chat sessions was the major barrier to this research. There are few suggestions on the time schedule for the chat sessions. They describe a successful use of chat but finding it difficult to arrange chat schedules. They want to schedule more chat sessions with longer time frame:

"I think the time scheduled for this experience was too short. What I mean is, there was not enough time to continue the dialogue about the project further on and really see how it was developing."

"I suggest also that the design studio coordination programs from beforehand all the chat sessions so that the most participants would be present at that moment. That would increase the exchange of the ideas."

"Assign time or block segments within the chat room time for the students to outline their problems, potential solution, present questions, or identify new web pages for the experts/responders to review, prior to soliciting responses from the experts. This gives experts the opportunity to review the items before responding."

There are few comments regarding the possible improvement on the user interface:

"I also had some problems with the scales of the drawings, as it was difficult to distinguish the details. Would there be some possibility to make observations directly on the drawing?"

6. CONCLUSION

The findings of this research indicated that synchronous chat may be a tool that is used to help architects design reviews in a distributed design environment. This research suggested that the synchronous chat sessions were useful in sharing design tacit knowledge. Specifically, the participants indicated that the design programming and initial brain-storming phases are more suitable for the use of synchronous chat. The students also felt that synchronous chat have benefited to help problem solving on design issues and have improved the overall quality of the design solutions.

Participants have clear expectations that synchronous chat could be integrated with visual display, such as "mark-up systems", of the design projects and that it would significantly may improve architectural design process.

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A COMPUTER-AIDED EVALUATION SYSTEM FOR INTEGRATING DESIGN- AND ORDERING-PRINCIPLES INTO PRODUCT MODELS

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Abstract: It is true that the commercial applications used in architectural offices have mainly focused on CAD as a drafting tool, although the primary functions of computers in architecture have been changed from the computer-aided drafting to its 2D or 3D graphic representation and in recent years to the collaborative design among different specialists, such as architects, engineers, construction managers, acoustical experts, and so on. There are still few computer-aided tools to help a designer in selecting the best suited design strategies, in particular satisfying the design aesthetics, and in connecting the design up to the collaboration. This paper shows how the design- and ordering-principles can be joined into a CAAD system and how the data of the applied design can be integrated into product modeling environment, providing the appropriate solution to the upcoming needs of the construction industry.

Keywords: Design- and Ordering-Principles, Collaborative Design, Product Model, IFC2x, Integration, CAAD.

1. INTRODUCTION

The building-industry is suffering from the high total-costs of its structurally non-dimensional products, which are relatively minimally automated, less computer-aided and, now as before, highly manual-labour orientated; these are wage-intensive products.
Efforts to improve qualities of an architectural design and simultaneously to reduce building- and completion-costs through comprehensive mechanical and computational technology have met with little success in the past, as has been the case in other branches of the economy.
Construction using computerised design-programs has great advantages in the two branches: design and construction in architecture. In the design aspect, the computational programs not only empower our imagination, but also provide opportunities for verisimilitude to support decision-making and for shortening planning-phases. In the construction aspect, this also has a lot of advantages, such as shorter building-time, greater precision (higher security standards for walls, greater strength in concrete), continuous machine capacity, resistance to the weather, dry construction-sites, the solving of complex details and surface cleaning by stationary saw- and planning-apparatus.
Along with this a problem arises: new elements in mechanically-prepared construction often appear unformed, due to soulless machinery. In other words, building, too, should meet aesthetic expectations.
Technology-guided construction has so far been unable to do justice to customers' needs concerning appropriate aesthetic form. Thus, this paper proposes an evaluating system that evaluates and advises on design qualities of architecture, using analytical design- and ordering-principles from traditional theories for the optimization of the architectural design from the aesthetic perspective. At this point, it must be assumed that the creative design, which depends on a human's own spiritual capability, lies with the designer himself.
Designs proposed by this system include optimum design qualities in terms of a traditional architectural theory, and new one which can be in future connected to product models. To do this, the definition of information about building elements is accomplished by using the neutral format EXPRESS-G, the graphical counterpart of EXPRESS [1], for such application systems.

2. PRODUCTION MODEL IN THE CONSTRUCTION

2.1 Overview of Product Model

It is widely accepted that the quality and efficiency of the design process in the AEC (Architecture, Engineering and Construction) domain can be improved only through increasing automation of the design and construction process. The key to success in achieving automation is seen as the integration of the information processing required by the various disciplines involved at the various stages of the design process; that is also the basis for collaboration. To do the collaborative work associated with each field, the communication aspect should be understood at least.
In order to enable this communication among actors,

for example, in the construction process, the data in each process have to be formally defined and standardized. In general, most of this issue is concerned with the exchange of project data. As there are many different CAD-systems and each CAD-software has its own internal description, we encounter difficulties when we try to transfer design data from one CAD system to another. In order to solve these problems, studies have been conducted since the beginning of the 1980s. These studies used the neutral-format files, such as IGES (Initial Graphics Exchange Specification) and DXF (Drawing eXchange Format). IGES has been evolving for over twenty years and has become a reliable and widely used format. However, it has serious limitations; it is restricted to partial geometry and annotation but does include structure and relationships. DXF is an Autodesk proprietary format that has been adopted by the construction industry. Similar to the case of IGES, DXF is not suitable for transferring partial geometry because of its lack of precision. As the next generation of IGES, the STEP (Standard for the Exchange of Product Model Data) is the international effort by ISO at trying to combine the different national activities in a single international standard.

2.2 STEP (Standard for the Exchange of Product Model Data)

STEP was born in December of 1983, when the International Standards Organization (ISO) formed the TC184/SC4 committee. STEP is an international effort to produce high-level standards for exchanging product information that support technical information exchange and communication within industries. STEP is targeted at the exchange of data describing a product between Computer Aided X (X = CAD, CAM, CAE, etc.) systems [2]. STEP product models are rich, structured, object-based data models of industrial products. They are generally designed to provide fairly complete, cross-application descriptions of product data, and the modeling methodologies for defining them are extensive and formal.

One of the best reasons of the success of STEP is the standardized EXPRESS language, which allows a complete and unambiguous description of information related to different conceptual components of a product. EXPRESS allows the designer to describe the data structure of the objects of his application, especially through the concept of entity describing a class of objects [3]. EXPRESS-G is a graphical notation for schemas defined in EXPRESS.

2.3 IFC (Industry Foundation Classes)

IFC is an information standard for the building industry, encompassing AEC/FM (Facility Management) domains. This standard is being developed by IAI (International Alliance for Interoperability) [4] whose mission is to define, publish and promote specifications for IFC as a basis for project information sharing in the building industry.

The IFC concept is based on the idea that objects are brought into an integrated model. These objects are defined in order to support the whole lifecycle of facility development from inception through design, documentation and construction, then facility management and finally to demolition and or disposal. The principal benefit of IFC is their object description – not only does the IFC protocol preserve the full geometric description in 3D, but it also knows its location and relationships, as well as all the properties or parameters of each object such as finish, serial number, material description, etc.

Part 11 of STEP, and the ISO EXPRESS language (STEP-11) have been adopted by IFC to describe its model. Thus, the IFC data model corresponds with the STEP standard and consequently contributes to the evolution that permits the exchange of building data between different programs. Unlike STEP, evolution is not planned for a norm, but aims at direct application in the industry. For example, the IFC has a much broader scope than AP 225 of the STEP. Work on the IFC model development has led to various releases of the model; IFC R1.0, IFC R1.5, IFC R1.5.1, IFC R2.0 and the release of IFC R2x. The current release (IFC2x) is focused on the design stages, but there is already support for facility management, and future releases will include thermal analysis etc. A subset of IFC is shown in Fig.1. It illustrates some of the entity definitions and relationships related to building elements, such as the decomposition structure, sub-types and associations with other objects [5].

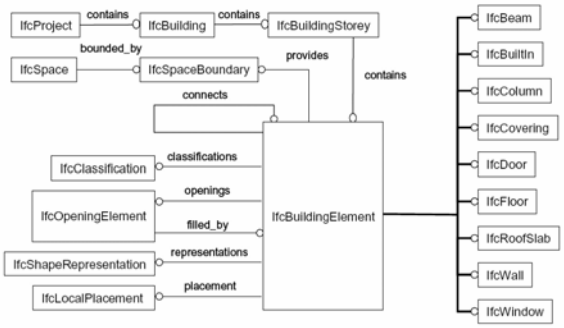

Figure 1. An interpretation of IFC, showing a subset with focus on the IfcBuildingElement

3. SCHEMA AND PROCESS OF THE SYSTEM

3.1 Conceptual Schema of the System in Product Model

The conceptual schema that plays a basic role in product models describes the process of the information about an architectural façade, which is needed for applying design- and ordering-principles to product models. A schematic view is shown in Fig.2:

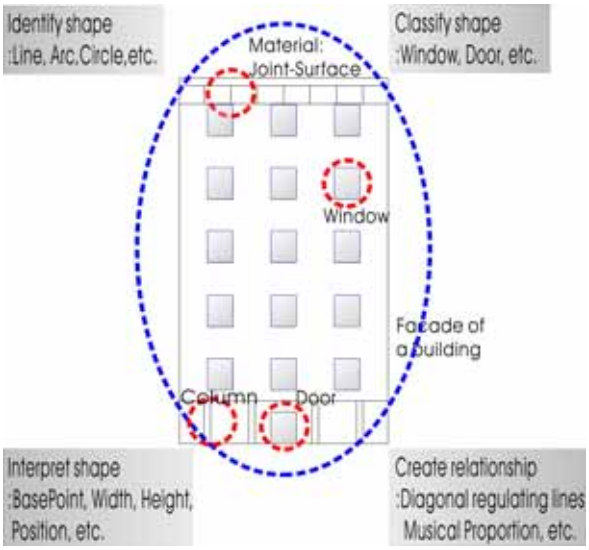

Figure 2. Conceptual schema of a façade

Four major sources of the information about a façade are described in Fig.2. These consist of:

- identifying shape: line, arch, circle, etc.
- classifying shape: window, door, column, façade, material of surface, etc.
- interpreting shape: base-point, position, width, height, etc.
- creating relationship: diagonal regulating lines, musical proportion, etc.

For implementation in a product model, each shape has to be defined and found in a drawing first. In general, a shape consists of a set of lines and curves which are usually connected. When each of the elements of a shape has been identified, it then has to be classified, in order to be recognizable by a computer by its own name, such as a window, a door, a column, etc. The interpretation of a shape is considered as the process that shifts the semantic content of the drawing to a higher level. Normally, this phase is one of main goals of IFC2x, and is the key to implementation of the application system in an object-orientated CAD-system; here, different aspects of an object are analyzed and stored as parametric values. When all elements of a façade have been recognized, their relationships can be analyzed and proposed by implementation of the AutoLISP. Thus, the design is "qualified", according to the optimum design- and ordering-principles.

3.2 Process for Development of the System

A process model provides a description of tasks needing to be undertaken. It defines all of the required tasks within the process and puts them in a logical sequence. The following process diagram illustrates the required scope of specification development for applying the architectural design- and ordering-principles to CAAD systems in the framework of a product model.

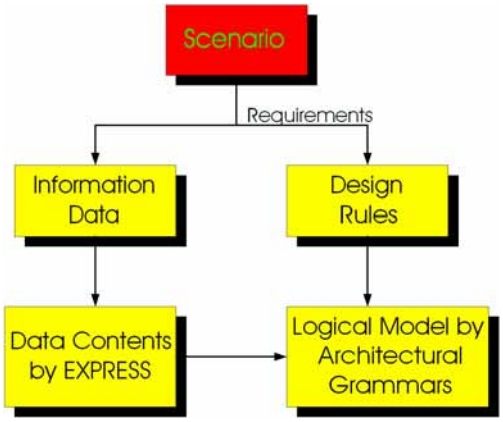

Figure 3. Process diagram of the product model

In this diagram, "Information Data" and "Data Contents" can be described with EXPRESS or EXPRESS-G, which give the fundamental information about a façade. In these phases, general entities, attributes and relationships between a building and its elements are defined. In the case of a building façade that will be examined, the hierarchical decomposition can be divided into structural layers, openings, surfaces and columns; the columns are described as optional attributes. These components of the façade can be defined with EXPRESS-G, as the following Fig.4:

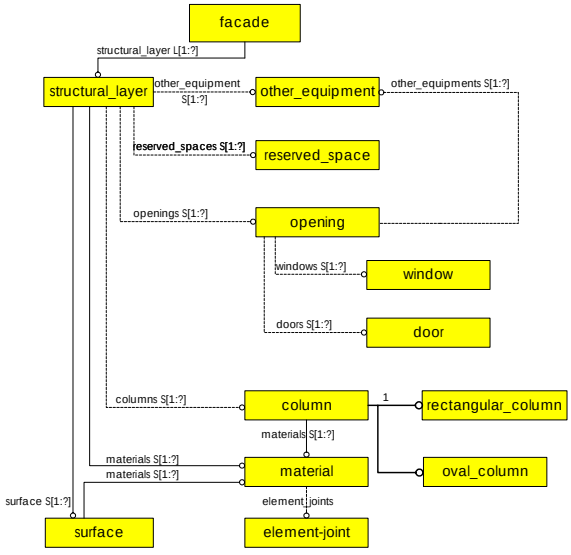

Figure 4. Overall EXPRESS-G diagram of the façade

This schema in Fig.4 contains physical parts of the façade that are related to each other element, which allows input of information about a façade in applications for design- and ordering-principles.

"Design Rules" and "Logical Model by Architectural Grammars" in Fig.3 are described in the following chapter 4.

3.3 Program Mechanism in the System

The programming language employed in AutoCAD is AutoLISP. As this language retains most of the general LISP (LIST Processing Language)-functions, it is a symbolic manipulation-based, interpreted language that provides a simple mechanism for adding commands to AutoCAD [6]. For example, this interactive programming language in AutoCAD allows users to program external applications, using the AutoCAD drawing generation and manipulation functions for 2D geometry, 3D wire-frame structures and 3D curved surfaces. Therefore, customizing AutoCAD into a more useful tool for a particular application for users can be carried out using AutoLISP programs. The AutoLISP program is normally written by "text editors" and then is saved as "text only" with the ".lsp" extension; i.e. rhythm.lsp. The main programming language of the proposed system in this work is AutoLISP. The system demonstrated here operates in MS-Windows XP and in the AutoCAD 2000 environment.

The choice of AutoLISP in this work has been made for several reasons: this author's amount of experience with both AutoLISP and AutoCAD; the reliable graphic control/output in AutoCAD and the worldwide usage of this system in architectural offices.

4. DESIGN RULE AND APPLICATION EXAMPLE

4.1 Design- and Ordering-Rule and Product Model in the System

Architectural theories in western architecture have been considered as a basis for answering the fundamental questions of architectonics: proportion, symmetry, color, harmony and so on. Among those the design- and ordering-principles are significant, since it affects the aesthetic evaluation of human's visual perception. In particular, the specific formal ordering-system, such as proportions, axes, grids, symmetries, etc., can help to maintain unity, to avoid chaos and then to achieve harmony in an architectural design.
In this paper, only the subsystem about rhythmic arrangement of windows among many design- and ordering-rules is described because of the limited pages. In general, rhythm in architecture is divided into two categories: even and odd rhythm. A very common symmetry is even rhythm such as 3, 5 or 7 time [7]. Above all, the use of 3, 5, 7 time is of greatest importance in the grouping of buildings. 3, 5, 7 time rhythm brings together and gives focus, thereby creating a considerably stronger impression of a form, moreso than 4, 6, 8 time rhythm, which continually threatens to break down into two or more parts; the latter permits a gap to exist within a maximum of two seqences of elements, for the creation of an axis of symmetry.
In short, odd rhythm, such as 3, 5 or 7 time, always has the power to determine symmetry through its center axis. This element "rhythm" alone can not achieve unity in a design. However, it contributes significantly to empowering the existing ordering principle. Representative kinds of different symmetrical time-rhythms in architecture are described in Fig.5:

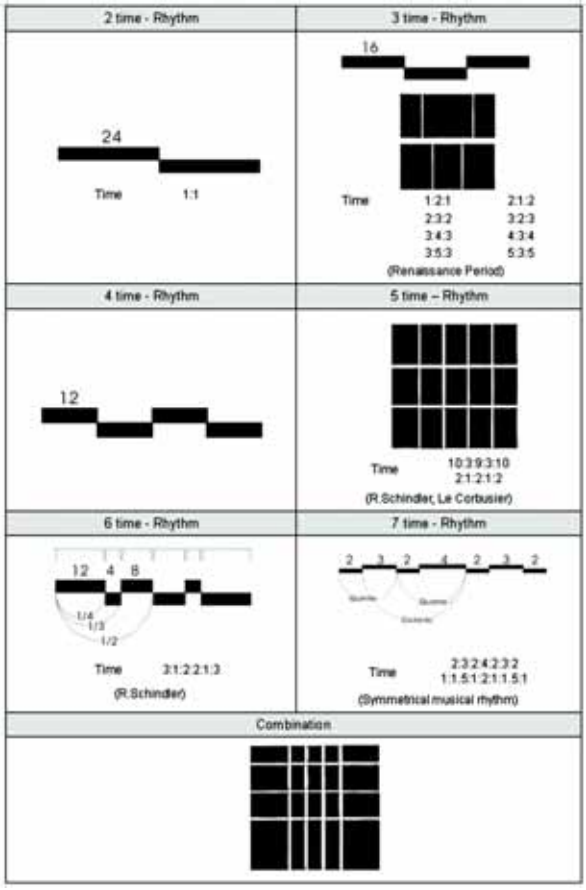

Figure 5. Different symmetrical time-rhythms

These time-rhythms as a design rule can be applied to the arrangement of building windows in a CAAD system. The base shape for implementation of the system is illustrated as following Fig.6.

In Fig.6, each relationship, A:B:C:D:E, on a façade can be calculated automatically through the computer, according to the mentioned symmetrical time-rhythms. For implementation of the system in a product model, a lot of information about this façade and its parts are needed, such as the length (L) and the height (H) of the building, each length (l) and height (h) of windows, distance (W1) from the building's edge to the edge window.

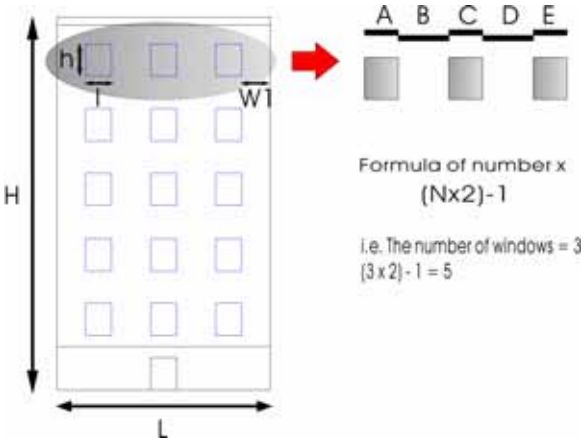

Figure 6. Basic shape for implementation of the system

The definition and value of this needed information are referenced from the already defined Ifc2x-model. The requisite entities for the symmetrical time-rhythms in the product model are as follows:

- TotalHeight of the Building: IfcQuantitiyLength
- TotalWidth of the Building: it can be measured from IfcQuantityArea
- OverallHeight of a Window: IfcPositiveLengthMeasure in the IfcWindow
- OverallWidth of a Window: IfcPositiveLengthMeasure in the IfcWindow
- Placement: IfcObjectPlacement (referenced entity: IfcLocalPlacement)
- Distance between Windows: it can be derived from the position of each juxtaposed window

The most definitions of entities of the façade correspond to the IFC2x. However, some entities were as yet undefined in IFC2x. These can be measured or derived from the existed IFC model, or can be newly defined.

4.2 Examples

The generated AutoLISP file can be loaded into AutoCAD. Then, the user uses "(rhythm)" in the command prompt to invoke the AutoLISP program to achieve harmonious arrangement of windows, which is based on the symmetrical time-rhythms.
While the AutoLISP program file is running, the command window of the AutoCAD asks the user for entering each needed value. The numerical value entered by the user is calculated automatically in this system, and the computer gives the user a number of design alternatives that are based on the time rhythm principle.

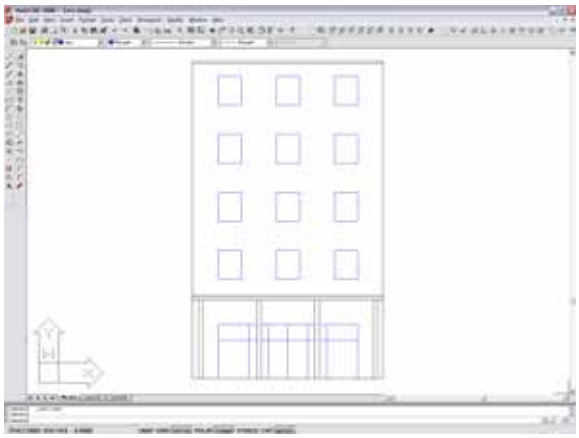

Figure 7. Original drawing of building façade

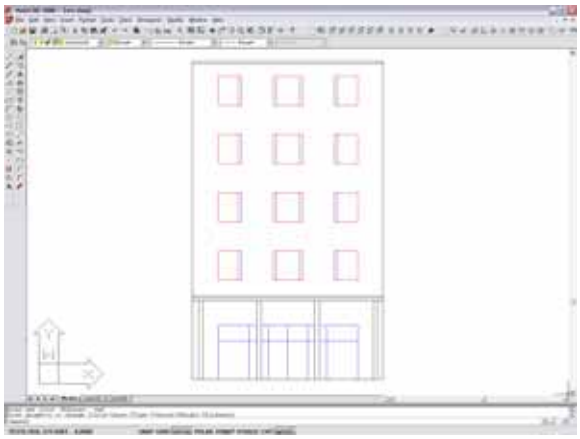

Figure 8. Design alternative that is advised by the computer

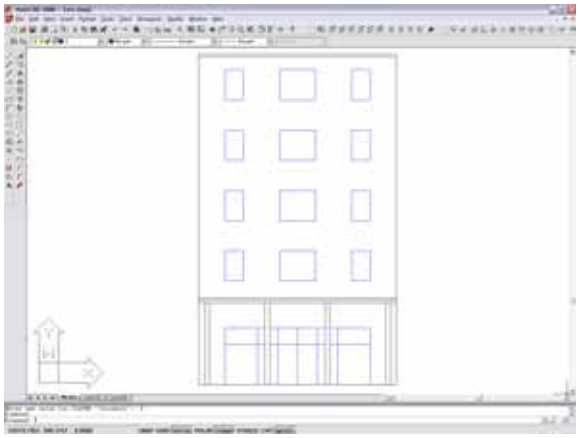

Figure 9. Final design based on the symmetrical time-rhythm

Fig.8 shows the screenshot of an alternative design among different ones which are advised by the system on the arrangement of windows.
The user can choose his preferred rhythmic relationship from those shown on the screen, according to his own design experience, as shown in Fig.9.

This system can be used as soon as it is needed and simultaneously the user can obtain some design advice from his own computer for a quality assessment of the particular design qualities.

5. CONCLUSION

As shown in the previous examples, the application system is applied to explain and develop aesthetic qualities of a design. Designs proposed by this system include optimum designs, which are based on the design- and ordering-principles, and on new ones which can be in future connected to a product model. The simple, visual rules used to develop designs are meant to explain how the designs are improved. Some problems are encountered during these tests. This proposed system has not been developed under the object-based CAD system, so that there are only series of lines, when any elements such as windows, doors, walls and roofs, are drawn in the existing CAD system; when one draws the outline of a shape, the drawing is always a line. This means that users must select each line that encloses an element in order to examine the relationship, for instance, between windows on a façade when implementing this system; the value of an element must be also chosen by users, clicking the mouse or entering the value on the screen.
However, the world's big CAD vendors, such as Autodesk, Graphisoft and Nemetschek, have recently started to offer object-based software, including the IFC2x model. They offer powerful CAD capabilities and significant building-design tools; e.g. when we add openings to a wall in this CAD software, the wall automatically adjusts itself to accommodate the openings and adds end-caps where needed. If we move the wall, the openings move with it. If we remove an opening from a wall, the wall repairs itself in the space where the opening was located. Therefore, the proposed system could be better enhanced, if it were developed using object-based CAD systems; it would neither need to select each element nor to click the length and height of an element.

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EXPERIENCES WITH A COURSE ON COLLABORATIVE DESIGN ON DISTANCE

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Abstract: In conceptual design of architectural artefacts, designers from different disciplines work together. Multi-disciplinary collaboration is required when buildings and their construction have a complex nature. If this collaboration is not effective and efficient, it might lead to the construction of buildings that clients disapprove cost too much regarding the delivered quality and extend the throughput time as well as raise failure cost. Collaboration in design take place in physical space, as well as in distributed, or virtual environments. Virtual design teams use a range of ICT tools to support both synchronous and asynchronous communication. While these tools are designed to facilitate collaboration, the collaboration process still requires planning and organisation, which is an activity that students and professionals need to learn. In current practice there is a need for designers and design managers with competences to collaborate in design and to organise distributed collaboration processes.
Keywords: Construction Management, Collaborative Design, ICT Tools, Experiential Learning.

1 INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry needs designers who are competent to design as a design team on distance. To acquire this competence, a course on Collaborative Design is developed at Eindhoven University of Technology in The Netherlands for students in the Master of Science curriculum on Architecture, Building, and Planning. The participating students have backgrounds that vary from design management, architecture, building physics, construction management, structural engineering, to urban planning and building information technology.

In this paper, the lecturers of this course evaluate the effectiveness of the course and reflect on how improvements are necessary and possible. The paper starts with a discussion on the critical aspects of collaborative design, the learning objectives of the course, and the approach followed. It then discusses our experiences and draws conclusions on improvements.

2 THE NEED FOR COLLABORATIVE DESIGN

Today's Construction Management needs competences for collaborative engineering and special for collaborative design. Harris and McCaffer stated that "Construction management has developed over recent years from a predominately site based activity into a highly integrated process that includes project conception, design, engineering, procurement and construction" [1]. In his inauguration lecture Schaefer pointed out the importance of knowledge management and collaborative engineering in describing the position of construction management [2]. Within the scope of automation and robotisation in construction the CIB Task Group TG27 "Human-Machine Technologies for Construction Sites" concluded that to get more performances in applying human-machine technologies there is a need for co-operating, partnering, collaborative engineering and design build [3].

This involves that actors in the mentioned domains need better competences in collaborative design and especially in collaborative design on distance because today actors are often separated by discipline as well as distance [10].

3 COLLABORATIVE DESIGN

One of the first issues in teaching collaborative design is to convey an understanding of what the term *collaboration* means. Kvan distinguishes between the terms collaboration and cooperation. In [4], he notes that *cooperation* relates to working together for mutual benefit, while *collaboration* relates to working together to achieve shared goals. The main distinction between the two forms of working together, according to Kvan, is the creative aspect of collaboration.

Kvan also distinguishes closely coupled design processes, in which participants continuously work closely to realise a design (see Figure 1), from loosely coupled design processes, where participants each

contribute from their particular domain expertise at moments when they have the knowledge required (see Figure 2). The latter model is observed more in practice.

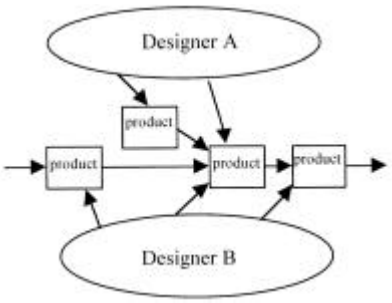

Figure 1. Loosely coupled design process.
(adopted from Kvan [4])

In the course presented in this paper, we stress that participants of collaborative design sessions in a multi-disciplinary team will make their own design thinking transparent and are able to listen with interest and respect to each other. They are willing to learn from each other and realise that only in this way a good and integrated design result can be achieved. The organisation of the design process is crucial here, especially when designers need to work on distance. They will make use of organisational instruments, such as meetings and scheduled tasks, as well as ICT tools for both synchronous and asynchronous communication and data exchange.

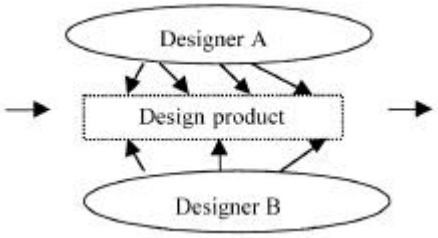

Figure 2. Closely coupled design process.
(adopted from Kvan [4])

4 COLLABORATIVE DESIGN IN EDUCATION

In educational master programmes on architecture and engineering, initially students often work alone on assignments, the results of which they discuss with their supervisor. When teamwork comes into play, students have to organise their activities and make a project plan. They have to find answers to questions such as: what are the general objective and problem; what is the approach followed; what is the planning; who does what; which results are expected when? At the authors' department, the skills to organise such a project are practiced in a multi-disciplinary design project in the third year of the Bachelor's programme.

However, as noted before, Collaborative design is more than working together in the sense of cooperating with individual tasks in such a project. Both organisational and technological issues are involved when a team needs to collaborate, particularly when collaboration takes place on distance. Questions that arise are: how do you organise a design meeting; what is the team members' organisational role as opposed to their professional role; which techniques can be used to enhance creativity in the group; how will we communicate on distance with respect to verbal and graphical communication; what about asynchronous communication? The Master of Science course 'Collaborative Design' developed by the authors, aims to teach these skills and to provide students with insight and knowledge in the particular complexities of (distant) collaboration in multi-disciplinary design projects.

4.1 *MSc Course on Collaborative Design*

The objectives of this course at Eindhoven University of Technology are to gain insight in the problem domain of collaborative design and to get to know the possibilities of methods and techniques to approach this problem domain. Methods and techniques concern both organisational instruments and ICT related tools. Specific competences that are acquired through this course are the following.

- To play an organisational role in a team-working project. This involves being able to identify social and organisational roles people play in teams and becoming aware of one's own role as assumed and as required.
- To play a professional role in a multi-disciplinary design process. Here the focus is on the activities and responsibilities of the students from the viewpoint of their respective expertise and specialisation.
- To work together in a design team. The critical issues here are the creativity in the team and the students' contribution to the creative process. An important aspect is for students to realise that creativity in a team of designers and engineers must pass the boundaries of individual disciplines; taking one another's viewpoints is essential.
- To be able to use, assess, and select relevant ICT tools for face-to-face as well as distant, and synchronous as well as asynchronous communication to support progress in the design processes.
- To reflect on the work of the team and on the student's individual contribution. The key to re-

flection is the student's awareness of the overall process as well as the individual activities and the roles and actions that the student has taken up.

The educational approach chosen in this course can be indicated as 'experiential learning.' This means that students acts as active learners while the teacher's coaching role is focused on observing student's activities.

According to the American Institute for Experiential Learning [5], this educational concept is composed of three components: knowledge, activity and reflection.

The activities in the course were organised into five assignments, of which two were individual assignments and three were group assigned design tasks:

1. *Literature review*. Each student prepares a summary and short presentation of a review of two scientific papers on the topic of collaborative design.
2. *Designing in a team*. In this task the student is member of a multi-disciplinary team. Within each of the six teams, students represent various construction-related professions, such as architect, structural engineer, contractor, principal, HVAC consultant, etc. (see Figure 3). The team designs the function of a building object in one or two face-to-face meetings. The result is a design brief.

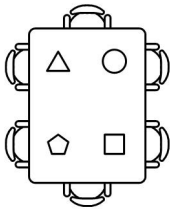

Figure 3. Task 2: Design in a multi-disciplinary team through face-to-face meetings.

3. *Designing in a distributed team*. The same multi-disciplinary team now works on distance and organises virtual meetings to design a spatial layout for the building object described in the brief from task 2. The virtual meetings take place through synchronous communication using a selection of ICT tools (see Figure 4).

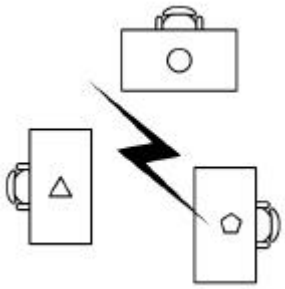

Figure 4. Task 3: Design in a multi-disciplinary team through online meetings and distributed work.

4. *Designing in a distributed organisation*. For this task, a re-organisation of the teams takes place. The various multi-disciplinary teams are re-organised into mono-disciplinary teams that represent each of the construction-related disciplines. While the students keep their original professional role, they are now teamed up with others that have the same role. Together these teams form an organisation of multiple professional disciplines (see Figure 5). The organisation's task is to agree on the final design of the building object, based on the designs previously made in task 3. The choice for a face-to-face or virtual meeting is open. The organisation as a whole has to deliver one final plan for the building.

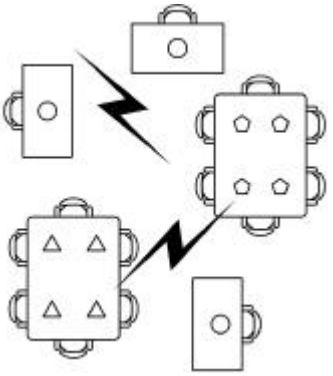

Figure 5. Task 4: Design in a distributed organisation of multiple mono-disciplinary teams.

5. *Individual final report*. Every student writes a report on his/her experiences with the course, describing what he/she has learned and providing an evaluation of the ICT-tools that were used.

The three team assignments were important in the course, but mainly as a way for students to gain experiences. For this purpose, the team sessions were not tutored. The way the teams addressed the organisational problems was completely left open. Lecturers would not actively involve themselves in the teams' functioning, but could be consulted at any time.

The individual final report formed the sole basis for the final assessments of the student's work in the course. This made it possible for students to experiment in the teams, while at the same time removed the mutual dependencies of students to successfully conclude the course. The team was allowed to fail: individual students were assessed by their perception

of the process and the personal actions manifested during the process.

The student workload of this course is 84 hours, corresponding to three ECTS (European Credit Transfer System). The course is described on the website and includes all necessary information about objectives, tasks, literature, time planning, relevant web links, requirements for deliverables, presentations, lecture notes, reflection criteria, etc. [6]. Students' contributions and the results of activities in the three design tasks were submitted through a Project website.

4.2 *Thematic lectures*

Apart from the assignments and the plenary discussions of the progress of the teamwork, the course included interactive lectures on the following four themes.

4.2.1 *Organisational and social aspects of designing in teams*

In these lectures, the objective was to make students aware of the many social aspects to collaboration, such as the need for mutual acceptation, openness, commitment to shared goals, shared responsibilities, etc. Becoming aware of the roles people can play in a team was an important issue. Students were asked to identify their own role according to the test developed by Belbin [7,8]. In this test, team roles are distinguished in three categories: action-oriented roles, people-oriented roles and cerebral roles.

Students found it useful to become aware of their own natural role in a team. It allows them to recognise their own behaviour, to take advantage of their natural strengths, and to be conscious with their natural weaknesses.

Another kind of role is the professional role that students play in the team. As the students have different backgrounds, the teams were multi-disciplinary teams. The multi-disciplinary design tasks allowed the students to play their professional role and experience how the nature of this role has an influence on their behaviour and in the relation with the other team members.

4.2.2 *The use of ICT tools for collaborative design*

Besides email and instant messaging tools that students are already accustomed to, the ICT tools that were mainly used in this course are Netmeeting (Microsoft), Architectural Studio (AutoDesk), and the Project website programme Automanager Meridan (Cyco Software).

All participating students own a notebook computer with software that is relevant and required for their study. The university campus, including many student residences, provides internet access, partially through a wireless network.

While the observed process can be represented by the schema in Figure 6, which is a modified version from [4], an additional activity was inserted in the schema to represent the synchronous communication that takes place while team members work individually on distance.

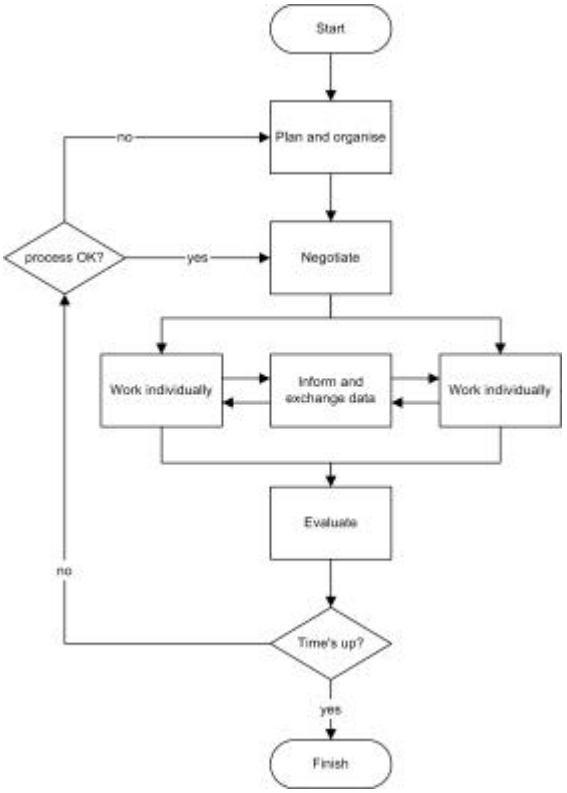

Figure 6. Collaborative design process. (modified from Kvan [4])

4.2.3 *Organising and managing the design process*

Apart from the group-level aspects of collaborative design, the course also addressed the issues of how to manage design processes and what kind of information environment organisations can deploy in design and construction projects. The potential of project websites was discussed with particular interest in the business implementation issues. The way that an organisation is adjusted to new tools and the drive to stimulate co-workers to accept them are of crucial importance for successful application of tools that are allowed to play such a central role in a company's core-business.

4.2.4 *Collaborative design in practice*

Practical experiences on Collaborative design were presented in the course by guest-lecture of the central process owner of a national governmental organisation with regional agencies on recently gained experiences of implementations and use of a distributed project website in the agency's daily practice on construction project management.

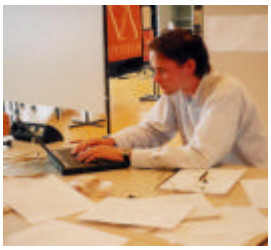

Figure 7. Students collaborating on distance.

5 RELATED COURSES

A course that is similar to the one described here is taught at the University of Florida and the University of Illinois at Urbana-Champaign. This course is called Collaborative Design Processes (CPD). O'Brien et al. describe the intention and organisation of the course and their experiences with it [9].

The objectives of this course are:

1. To understand the group dynamics and to develop negotiation and decision making skills through direct experience of group design work and through critical reflections, evaluation and analyses of multidisciplinary, net-based collaborative design processes.
2. To complete a facility design including a plan, schedule, budget, and structure using different work processes enabled by the use of information technology.
3. To learn how to evaluate and integrate technologies of multi-disciplinary remote collaboration in AEC design projects.
4. To design improved work process methods and to make recommendations for the development of improved software tools for collaborative, multi-disciplinary design.

The main differences with the course described in this paper are:

- The course by O'Brien involves a higher level of detail of the required end-results from the design assignment.
- Their course is based on Bricsnet's Project Center rather than Automanager Meridian and AutoCAD instead of Architectural Studio.
- Their course is focused more on technical aspect of the distant collaboration and not so much on the social aspect.
- In the course by O'Brien, the personal reflection is an informal document, whereas in the author's course the student's individual reflection is the main means for assessment.

6 COURSE EVALUATION

The course was taught in 2003 and in 2004. To be able to assess and improve the course it was necessary to evaluate both content and format. The type of questions that an evaluation of the course should provide an answer to were:

- Is the educational approach effective and do students actually acquire the targeted competences?
- To what degree have students been able to develop themselves with respect to the domain of collaborative design?
- Have they acquired sufficient skills using the tools for distant collaboration?
- Are students capable of using the tools on their own initiative?
- Have the students been able to integrate the organisational and technological skills in their work?

Answers to these questions have been obtained in two ways. First, the individual reports of the students contained information regarding their personal reflection and learning experiences. Second, a formal evaluation was carried out in 2003 and 2004 by the department's educational support section.

In the students' reports, we extracted information regarding the collaboration process during the three design assignments, analysis of these processes in terms of activities, roles, and tasks, and their experiences in participating in the design team using organisational instruments as well as ICT tools.

The formal evaluation was carried out by a departmental evaluation officer in the form of a written enquiry among all participating students. The results of this enquiry give insight in the perceived relevance of the course objectives, the quality of the course and the assignments, the time spent by students, the leaming yields, etc.

6.1 *Evaluation results*

The main conclusions from the evaluation based on the individual reports by the students are:

- Most students were aware of having experienced different organisation of design processes as well

as using different organisational instruments and ICT tools to be effective.
- Working in a team of people previously unknown to each other has a significant and positive influence on the learning experience.
- Students were actively aware of the roles they played in the team; this concerned both the role as a team member (e.g. according to Belbin) and the professional role in a multi-disciplinary team.
- It appeared difficult to be aware of, or even to play, both types of role at the same time.
- Playing the professional role is difficult because of the unrealistic setting in an educational project.
- Organisation of the collaboration is crucial for the success of the process.
- Reflection is the most difficult part of the experiential learning format that was applied in this course. A reason might be that students don't have much experiences with this instrument.
- Sufficient skills with ICT tools are necessary: lack of skills will frustrate the collaboration process.
- Physical distance is necessary to enforce distant collaboration (if they can easily walk and meet, they will).

Conclusions derived of the formal evaluation:
- Reflection is an effective instrument to finalise such a course. It helps to intensify the learning effect for both students and lectures.
- Students appreciate the combination of social and technical aspects of the course: 50% of the students appreciate the balance between technical and social/organisational issues in the course. 25% find the course too social, 25% find it too technical. Around 50% of the students find the combination of these issues the most interesting aspect of the course.
- Students appreciate the completeness of the course material on the website.
- Students rated this course by 3.5 (was 4.2 in 2003) on a scale 1-5.
- The appreciation for the ICT tools varied: 26% too simple, 32% too complex and 42% effective.
- Teamwork on the assignments was largely untutored. 60% of the students agree with this approach and have no need for intense guidance during the design tasks.
- Students found that the format of the course stimulates their active participation.

7 CONCLUSIONS

A general conclusion after teaching this course for two consecutive years is that a satisfactory level of collaboration is not easy to achieve with students that are traditionally trained in cooperation and coordination. Much effort is needed to convey the notion of collaboration in different settings specifically distant collaboration. Experiential learning is a very good way for students to learn the need for, e.g., organising effective collaboration processes. Providing students with theory and examples, and also discussing such issues in groups, does not lead to the same effectiveness in learning through experience.

Future development for course improvement will focus on redesigning tasks and probably adding smaller exercises as well as exercises focused on effective use of ICT tools for distance collaboration. Adding smaller exercises will focus on a more limited number of aspects of collaborative design. For example, separating the focus on organisational roles from that on professional roles is preferable in early exercises. They can be combined in later exercises or assignments. This is likely to increase the awareness of the differences and the influences on students' behaviours.

While experiential learning was successful, the effect can probably be increased by informing students about the approach and the expected effect.

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ARTIFICIAL LIFE-BASED HOUSING DESIGN ASSISTANT FOR NEW CONSTRUCTION PARADIGM USING SMART PARTS

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Abstract: This paper proposes a life cycle oriented construction system that considers each construction parts; walls, bath units, kitchen utilities and other facilities as primitive artificial life (AL) forms consisting of a more complicated artificial life form, i.e. the house. As a start, we developed AL-based housing design assistant software that let AL-forms connect and construct house floor plans in 3-D virtual space, and AL-based remodeling design assistant software that wakes dormant AL forms up to re-generate new design plans. Those two of design assistant software are evaluated by questionnaires with mock customers.

Keywords: Artificial Life, Life cycle oriented construction system, smart parts, Movable Finite Automata, Housing design, Remodeling, Design preferences of customers, RFID

1. INTRODUCTION

We developed design assistant software using an AL theory. This study is a part of the Innovative and Intelligent Parts-Oriented Construction (IF7-II) project [1][2], sponsored by the Ministry of Economy, Trade and Industry, Japan. The aim of the project is to propose a new construction paradigm utilizing construction parts with ICs, called smart parts.

As a part of the new paradigm, a life cycle oriented construction assistant system was proposed and reported [3][4][5]. The life cycle of a building may consists of multiple phases as, design, construction, delivery, maintenance, remodel, reuse and waste (Fig. 1). The smart parts are capable of contributing to the health of the building throughout its life cycle with information that they contain.

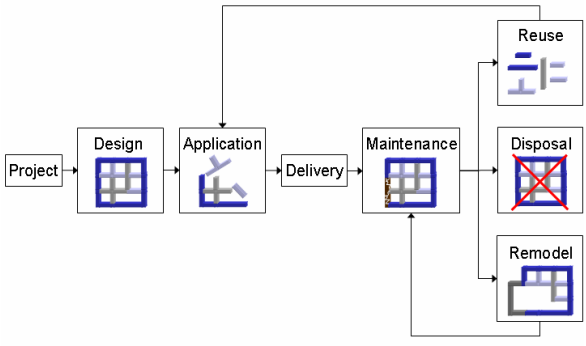

Figure 1: A life cycle of a building

The life cycle oriented construction assistant system takes advantage of this feature of the smart parts, noting that the smart parts can be considered as primitive artificial life-forms. For example, they can automatically construct the building in the application phase, and reconstruct another building with original design information and behavior in remodel phase. The system fully utilizing those AL-forms will increase efficiency of construction greatly.

As a start, we chose two phases of the life cycle: the design phase and the remodel phase. Information and behavior of artificial life forms are settled first in the design phase, and those are used again in the remodel phase. Since the latter is a re-design phase of a house, it is efficient to develop those two design assistant software packages together.

The software generates housing design plans using Movable Finite Automata (MFA), which is a branch of artificial life theories, to artificial life forms such as inside wall parts, bath units, kitchens, and other facilities. Those construction parts are important to characterize the generated design plans.

The design assistant software also can help customers to clarify their preferences. Most of them cannot express their preferences explicitly either in the design phase of in the remodel phase because of a lack of professional knowledge on construction. Instead, they show their preferences on room layouts in words like “3LDK” or “a large south side living room.” It is also the case in the remodel phase that customers can only state their troubles in the houses they live in instead of telling how the house should be remodeled. The proposed design assistant software packages are able to process both of such vague requests and dissatisfaction of a customer and to generate various housing design plans that satisfy their requests or solve their problems.

They are also capable to show the plans not in 2-D diagrams but in 3-D graphics in order to enable customers to easily recognize characteristics of the design plans. From those design plans, customers can choose suitable ones according to their preferences. This can also help an architect to understand the customer's preference more specifically, which is a non-trivial job and time consuming. Thus the proposed system can contribute in reducing both the total construction

time and money.

In this paper, we will give a summary of our two design assistant systems including rules and attributes given to AL forms so that they can adopt customer's preference in emergently creating design plans. Capabilities of the developed systems in reflecting customer's request is evaluated by running the system with requests of mock customers. Their responses to questionnaires on generated room layout plans are analyzed and results are presented.

2. ARTIFICIAL LIFE

2.1. Overview

In [6], it is stated that 'Artificial Life is the study of man-made systems that exhibit behaviors characteristic of natural living systems.' 'The behaviors characteristic of natural living systems' can be constructed by top-down approaches, as former theories in Biology did. However, AL theories generate them by bottom-up approaches. This feature of AL relates to 'emergent behavior,' which is a main feature of AL. Because of this feature, AL can provide variety of solutions for a problem it is applied to.

2.2. Movable Finite Automata (MFA)[7]

The proposed software generates multiple design plans using MFA, a technique of AL, where a floor plan is emergently generated by autonomous interaction among artificial life-forms, called automata and representing inner walls and room fixtures, in a virtual field, representing the construction space. In the behavior model of automata with MFA, each automaton has several bond sites on its body. If there is a complementary relationships between two bond sites of different automata, those bond sites form a bond and those automata connect to each other (Fig. 2). This 'complementary relationship' can be expressed as a relationship between a key and a keyhole. In this study, any bond site of automata is given either a key attribute or a keyhole attribute. A bond site on an immobile automaton is given a keyhole bond site and fixed in the virtual space. An automaton with key bond sites can move around and searches automata with a keyhole bond site to connect. Once connected, an automaton with the key bond site seizes to move and the pair of key and keyhole bond sites become dormant. Another keyhole bond site is generated on the 'edge' of the connected automata synchronously. The new keyhole bond site becomes ready to accept an automaton with the key bond site (Fig. 3).

Basically, this process is repeated until a new room plan is completed or pre-specified time duration is over. It is noted that, by the nature of AL technique, there is no global rule that governs how a new room plan is formed and that guarantees variation in generated room plans.

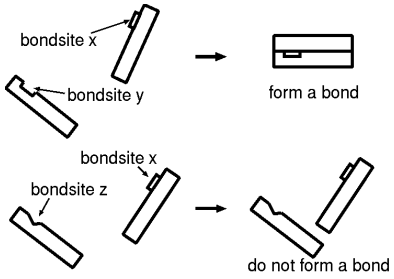

Figure 2: An example of relationships between bond sites: Shapes of bond sites express visualized complementary relationships.

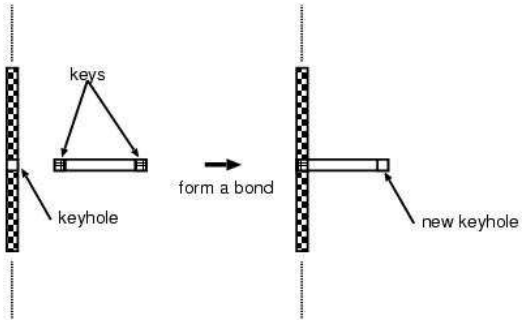

Figure 3: Induced keyhole on parts

3. DESIGN ASSISTANT SYSTEM

In this chapter, the design assistant system that generates floor designs according to customers' preferences is described.

The design assistant system for the design phase generates floor plans that are essential to housing design based on rough preference of customers. As discussed above, they show their preferences on floor plans in words like 'xLDK' where x denotes a number of rooms for individuals and "LDK" denotes a composition of a living room, a dining room, and a kitchen. Or they may say in words such as 'a large south side living room' that denotes ambiguous preference of rooms that have some important purpose.

Those words represent customers preferences or purposes of rooms such as: rooms for a family (e.g. living rooms or kitchens), rooms for individuals (e.g. bed rooms or study rooms), and rooms to connect each room and outside of the house (e.g. corridor or entrance). Also, in the case of average sized houses, most customers prefer rooms of the same purpose being nearby to each other. This observation leads us to divide the virtual space into three areas according to those three purposes of rooms: Family Zone, Private Zone, and Entrance & Corridor Zone. Thus, the rooms generated in the same zone have the same purpose as shown in Fig. 4.

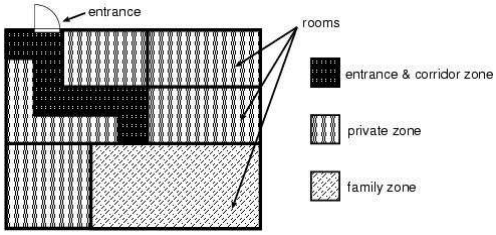

Figure 4: Relationships between zones and rooms

Customer's preferences on the floor plan are obtained according to the categorization of rooms.[4] The system takes preferences of

- numbers of big/medium/small rooms for the family and individuals
- location and general extent of an area for rooms for the family

as inputs from a customer. Customers can express the latter preference by drawing a circle to indicate the general location (Fig. 5).

The developed system takes the set of those preferences as an input to define the attribute of the artificial life-forms. Two methods are developed. Version 1 divides the interior of the house into two regions, excluding the corridor & entrance region, similarly as the partition of the outer walls. Then the floor plans are generated for two regions separately (Fig. 6).

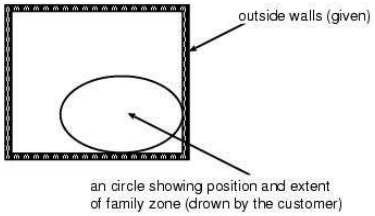

Figure 5: An example of drawings showing a preference of a customer for position and extent of Family Zone

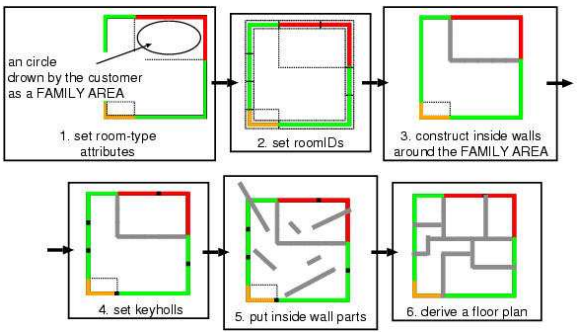

Figure 6: Process flow of Version 1

In Version 2, a corridor from the entrance to the area of rooms for the family is generated first before other rooms are formed (Fig. 7). The location of the entrance is chosen by the customer and is marked on the outer walls prior to this operation. The process of floor plan generation with MFA is shown in Fig. 8 for version 1.

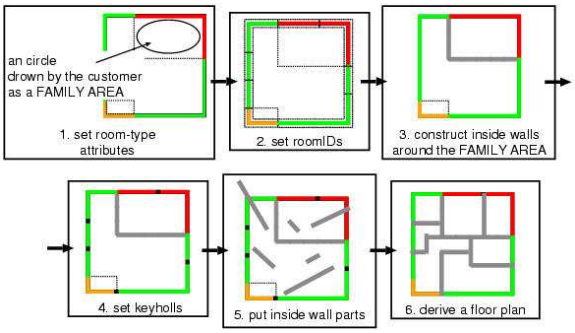

Figure 7: Process flow of Version 2

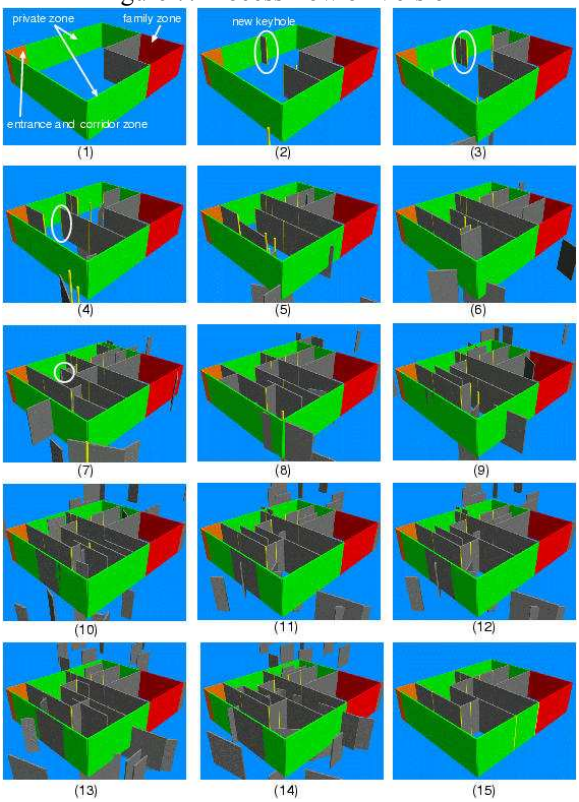

Figure 8: Process of floor plan generation by the developed system with Version 1

4. REMODELING DESIGN ASSISTANT SYSTEM

The design assistant system for the remodel phase considers expansions of the house and replacement of kitchen utilities, a bath unit and other facilities in addition to generating new floor plans. The processing flow of the developed assistant system is shown in Fig. 9.

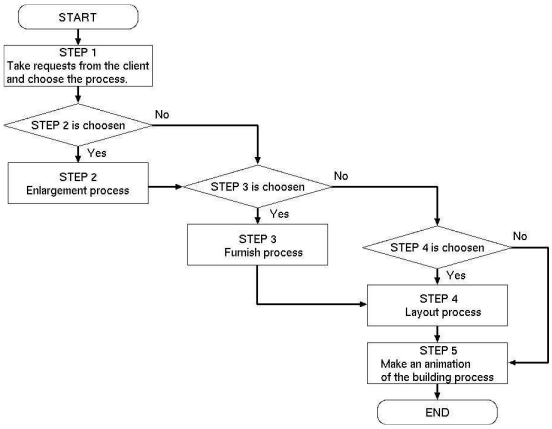

Figure 9: Processing flowchart of the system

The developed assistant system has a user friendly GUI for customer input session (STEP1). A customer can enter such items as:

- the number of bedrooms and type of combination of a living room, a dining room and a kitchen (Fig. 10)
- the area of the house that should not be remodeled (Fig. 11)
- general direction of water related rooms and facilities
- problems with his/her current house (Fig. 12)

It is noted that the system can consider complaints of customers who don't have enough professional construction knowledge to find out critical solutions for those complaints. According to problems chosen by them, the system chooses a set of solutions from expansion, refurnishing, and reconstruction of the floor plan (Table 1). Those pages of GUI are helpful for customers to express their preferences.

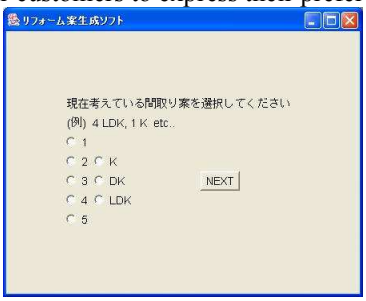

Figure 10: A GUI for client inputs on number of bedrooms and type of L, D & K

Figure 11: A GUI for determining exempted area from remodeling

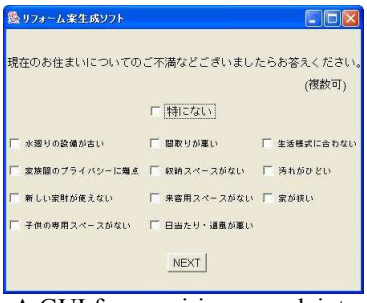

Figure 12: A GUI for acquiring complaints of the client on the present house

Table 1: Problems and corresponding solutions for remodeling

Problems	Solutions		
	Step2	Step3	Step4
Not enough living space	○		
Bad floor plan		○	○
Mismatch between floor plan and lifestyle		○	○
Lack of privacy		○	○
Cannot use new household articles		○	○
Need an exclusive space for children	○	○	○
Fixtures of bath room and toilet and kitchen are old			○
Bored with current house	○	○	○

The system takes the design of the current floor plan, which is generated by artificial life-forms in the design phase and is an aggregate of dormant artificial life-forms (e.g., inner walls, outer walls and household facilities), as the basic input. It not only selectively revives inner walls in the area chosen for remodeling but also selectively activates outer walls of the area chosen for extension and household facilities in the remodeling area.

It can also utilize existing CAD data of facilities, from their manufacturers' catalogues to replace the ones in the current house plan. This function enables customers to evaluate both new floor plans and new facilities in a realistic setting. A set of a current floor plan and a remodel design plan based on the current floor plan is given in Figs. 13 and 14.

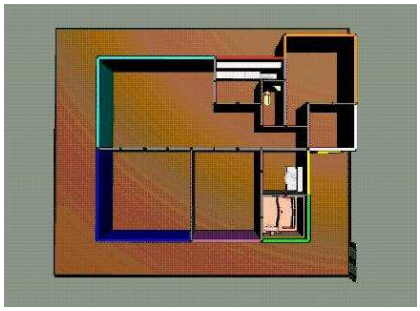

Figure 13: An example of a current floor plan

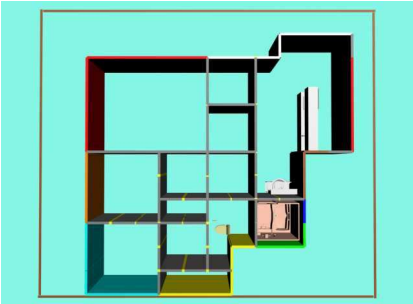

Figure 14: An example of a derived remodeling design plan from the plan in Fig. 13

5. Evaluation of Developed Assistant Systems

Capabilities of the developed systems in reflecting customers' requests are evaluated by running the both systems with requests of mock customers whose ages are over 20s to 60s.

5.1. Evaluation of Design Assistant System

We adopted two house shapes, House Shape A with rectangle shape and House Shape B with an indented corner, for evaluation experiments. Preferences listed in Chapter 3 are taken for the two house shapes from each of a set of 14 mock customers. An example of a set of customer responses is listed in Table 2. Floor plans are then generated and shown to the mock customer. Evaluation is done by asking the mock customer to answer a questionnaire on the four generated floor plans for each of two house shapes (Fig. 15).

Table 2: An example of a set of mock customer preferences (used for generating floor plans in Fig. 15)

	Family Zone			Private Zone		
sizes	L	M	S	L	M	S
number	1	1	0	1	1	1

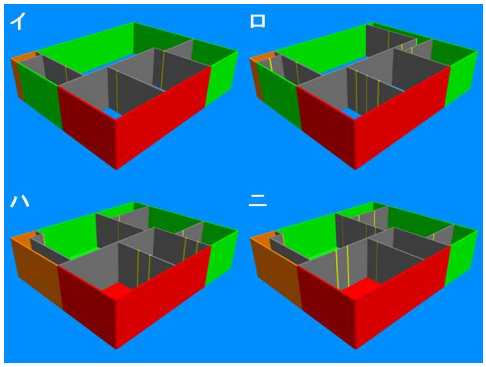

Figure 15: An example of a set of four generated floor plans for House Shape A

As the results of questionnaire in Tables 4 - 7 show, customer evaluations are satisfactory in most questions on how well the generated floor plans reflect the customers' preferences. Those results prove that preferences for Family Zone are well-reflected in floor plans. Preferences for Private Zone are, however, reflected not as well as the ones for Family Zone. We found, from the comments of customers, that scores for rooms in Private Zone can be improved by restricting room shapes to be rectangle and by avoiding too narrow or too wide rooms. Also, general acceptance of floor plans generated by two versions is about the same with a slight advantage in Version 2 with a corridor. This result suggests better prospect for Version 2.

Table 3: Scores for the location and extent of Family Zone

Score	Total Number of People	
	House Shape A	House Shape B
5	9	10
4	2	2
3	3	1
2	0	1
1	0	0

Table 4: Scores for the composition of big, medium, and small rooms in Family Zone

Score	Total Number of People	
	House Shape A	House Shape B
5	38	16
4	10	20
3	7	10
2	0	8
1	1	2

Table 5: Scores for the composition of big, medium, and small rooms in Private Zone

Score	Total Number of People			
	House Shape A		House Shape B	
	Ver. 1	Ver. 2	Ver. 1	Ver. 2
5	1	7	1	7
4	6	6	7	10
3	13	4	16	7
2	6	10	3	4
1	2	1	0	0

Table 6: Scores for the best room and the worst room in the four floor plans

House Shape	A		B	
Version	1	2	1	2
Number of the best room layout plans	4	10	8	6
Number of the worst room layout plans	6	8	9	5

5.2. Evaluation of Remodeling Design Assistant System

The same questionnaire is also used for evaluation of the remodeling design assistant system except that three remodel plans are shown for a mock customer. In this questionnaire, most customers state high scores for improvements of current problems (Fig. 17). Particularly high scores are obtained for a question on degree of variations in generated plans (Figs. 18 - 19).

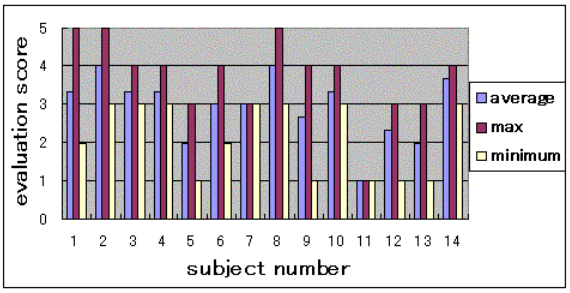

Figure 17: Improvements on current problems

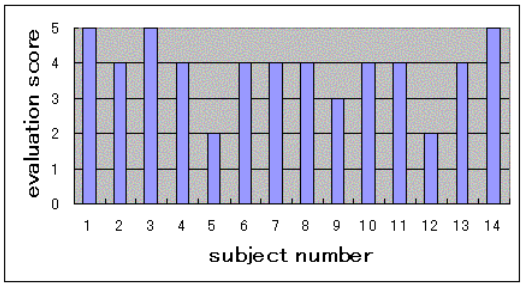

Figure 18: Diversification in room sizes

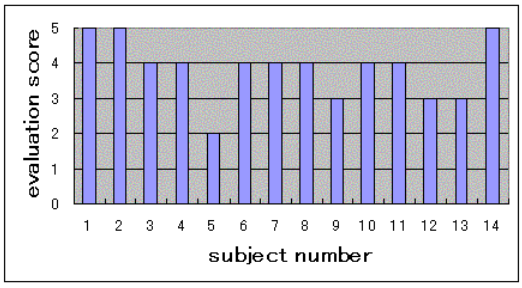

Figure 19: Diversification in room positions

5.3. Discussions on Evaluation of Both Design Assistant Systems

The results of questionnaires for both systems imply that the both systems can generate variety of floor plans. This endorses the intended capability of the floor plan generation engine that is common to both systems. It is also found, as expected, that the variation in floor plans is more limited when the set of preferences of the customer is more specific. It is also observed that rooms with irregular shapes are not popular among the mock customers. This gives rise to a need for a scheme to restrict chances of generating odd shaped rooms.

6. CONCLUTIONS

We developed two design assistant software packages, the design assistant system for floor design generation and the remodel design assistant system for remodeling design generation. Together, they can help both customers and designers in the initial design phase and the remodel phase. Those systems take customers preferences and complaints into consideration and use them in generating various design plans with an artificial life theory called MFA. The developed systems are tested with a set of mock customers and the derived design plans are evaluated by a questionnaire. The results of questionnaire endorsed the validity and the prospects of the developed software.

Acknowledgments

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DEVELOPMENT OF AN INTELLIGENT 3D PARAMETRIC MODELING SYSTEM FOR THE NORTH AMERICAN PRECAST CONCRETE INDUSTRY: PHASE II

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Abstract: 3D parametric modeling technology was first introduced about 15 years ago, but still only a few sectors in Architecture, Engineering, and Construction (AEC) have successfully adopted the technology in production. This paper reports the second phase of an early successful collaboration project between an industry sector, academia and a CAD vendor to develop an intelligent 3D parametric CAD system for the precast concrete industry in North America.

Keywords: parametric modeling, intelligent CAD, precast and prestressed concrete

1. INTRODUCTION

Automation of design and detailing in construction with intelligent 3D modeling instead of 2D drafting is beneficial in enhancing engineering and production productivity [1]. The Precast Concrete Software Consortium (PCSC) has pioneered development of an advanced 3D precast concrete building modeling system. The PCSC consists of major precast concrete producers in Canada and the US. The goals are to fully automate and integrate engineering, production, and construction operations, to gain productivity, and ultimately to increase market share. The first three authors are the technical advisory team to the PCSC, led by Charles Eastman at Georgia Tech.

The first phase of the PCSC project began in 2001 with a study of precast concrete processes, critical process cases, and the definition of a request for proposal to develop a precast concrete design and production software system based on parametric modeling. An 88-page request for proposal (RFP) with the business and technical requirements [2] was generated and distributed to major CAD vendors. The vendors included Autodesk, Bentley, Nemetschek, DiCAD, EDS-PLM (Unigraphics), Solidworks, and Tekla. After an eight month review of 12 proposals, the proposals were shortlisted to five, then two finalists. Tekla, with a strong 3D parametric CAD engine and the engineering and detailing capabilities for AEC, was selected as the precast CAD platform developer. The second phase began in April, 2003. More than 30 detailed technical requirements specifications were developed collaboratively by the PCSC, Tekla, and the Georgia Tech - Technion team.

The progress and findings from the first phase of the PCSC project have been reported and discussed in several places from various perspectives [2-9]. This paper reports the progress made in the second phase of the PCSC project, in which the PCSC members, the Georgia Tech - Technion team, and Tekla, have collaboratively organized and specified precast-concrete-specific functions that are required to automate design and detailing of precast concrete pieces. This paper describes the technical requirements for transforming generic parametric modeling functions into practical solutions used for the North American precast concrete industry. As of June 1, three beta versions of the advanced precast concrete CAD system have been released based on the technical specifications. Member companies have ghosted real projects using the beta versions. Results from pilot projects indicate that *engineering productivity* can be more than doubled [10]. This paper also briefly reports the results of pilot projects.

2. DETAILED TECHNICAL REQUIREMENTS SPECIFICATION

In order to automate design and detailing, a system must be *intelligent*. By *intelligence*, we mean “the ability (of a CAD system) to “maintain semantic integrity. The system helps keeping the representation of the evolving design consistent with its meaning ” [4]. However, the *intelligence* of a CAD system comes from domain expertise, not from within a system itself.

The first challenge we faced in the development of an intelligent CAD system was to collect and develop detailed technical specifications from domain experts.

It was also necessary to prioritize the required functionality, as project scope did not allow implementation of all the functions that were desired by the members. The priorities of development items were set by a matrix of the following three considerations:

- *Development effort*: how much effort is required to develop the function (in terms of work hours)?
- *Commonality/criticality*: how common or critical is the function in producing real precast concrete projects?
- *Effectiveness:* As a conclusion, how beneficial is a function in productivity gain and error reduction?

The significance of each criterion is relative. Many software functions may be important in modeling and automating real projects. The importance of functions must also be balanced with development costs. Some functions may take much longer to develop than others. However, any function that is essential for accomplishing a project must take priority over other development items that may enhance productivity, but can be 'worked around.' *Warping* is an example of an essential function. (See Section 2.2 for more information on warping).

Based on the above three criteria, preliminary development items were selected and specified in the *preliminary development item outline specification* as part of the official contract between the PCSC and Tekla. The arrangement was that the PCSC's technical committee would help Tekla to collaboratively generate detailed functional/technical specifications based on the earlier preliminary development specification [7] by providing needed precast domain expertise. In return, the PCSC companies were offered a significant discount and service as favored customers.

The preliminary development items were grouped in the following eight task groups for detailed specification:

1) Piece Modeling and Numbering
2) Connections & Joints
3) Surface Treatments
4) Building Assemblies
5) Drawings and Reports
6) Embeds
7) General Modeling
8) System Functions

A major challenge for collaboration in the development of the specifications was the geographic dispersion of the participants. Offices of the PCSC member companies, the Georgia Tech and Technion team, and Tekla were dispersed over 15 different locations across four countries (Canada, the US, Finland, and Israel). Various communication methods, e.g., weekly teleconferences, bi-monthly 3-day meetings, and a highly interactive custom-made website, were deployed to facilitate the collaboration across continents. The website included discussion forums, repositories for reference materials (drawings, reports), and e-mail distribution and other functions. In all, 397 MB, (1,655 files) of drawings, documents, reports, tables, and figures were collected and compiled through 447 distinct discussion threads. The website has been developed and maintained by the Georgia Tech team since the PCSC project's inception. The website was enhanced and customized as the interim goals of the consortium changed through each phase of the project. There were several mechanisms to promote collaboration on the project website: a history log, hit counters for each posting, search functions, various view options, a 3D model webviewer adapted from Tekla's Webviewer, and more. The PCSC project website can be found at http://dcom.arch.gatech.edu/pci.

Currently, as the role of the consortium is being transformed to that of a user group, several parts of the PCSC website are slowly migrating to Tekla's new user-forum website.

The following sections introduce the major precast-specific domain expertise and required system functions specified through the collaboration between PCSC, the Georgia & Technion team, and Tekla.

2.1 Parametric Piece Definitions

A major advantage of parametric modeling is its ability to embed intelligent object behavior without complex programming. However, if every building object and its behavior needed to be designed and implemented by users, the effort would be very time-consuming and error-prone.

It becomes very difficult to implement certain intelligent behavior in a system without pre-defining domain-specific objects. For example, if we want to develop a function to automatically design a connection between two precast concrete pieces (e.g., a connection between a *beam* and a *column*), a system should be able to distinguish a primary member and secondary member. Core precast concrete objects should be predefined at an abstract level. We call them *Abstract Function Objects (AFOs)* [3]. Later, users can develop their own custom pieces (such as column and beam) as an instance of an AFO to designate primary and secondary objects.

Major precast concrete products, which were defined through the requirements specification phase, include double tees, spandrels, hollowcore, beams, foundations, columns, walls, and stairs. Drawings and examples of each product type were collected and categorized. Their parametric definitions have been specified.

2.2 Special Piece Modeling Functions

There are generic modeling functions that are

required by most products whereas there are industry-specific "shape transformation" functions that can greatly reduce users' efforts and time to model certain types of products. Many precast concrete products require shape transformation functions because their shape in production is not the same as their shape in situ. All prestressed pieces experience elastic shortening once they are stripped from their forms. Some also have a camber (vertical plane curvature along their axis) if the prestressing is eccentric. In addition to these two transformations, double-tee floor pieces are also often intentionally warped along their length in order to create slope for drainage (Figure 1).

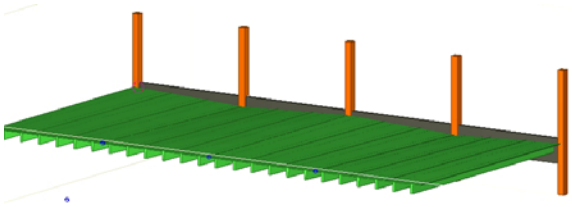

Figure 1. Warping of Precast Concrete Slabs (Note the depression of the slab at the second and fourth columns).

If these shape transformations are not properly considered in the design, engineering, and production phases, the produced pieces will not fit correctly: they could also be too short, too long, or too curved. when they are delivered to a construction site. Currently, these shape transformations have to be calculated by hand. But with the 3D geometric definition of a precast concrete piece, this is one of the engineering calculations that can be easily and efficiently done by the system.

2.3 Piece Numbering Schemes

Precast concrete pieces are managed and controlled by different identifiers at different lifecycle phases. In the schematic design phase, a precast concrete piece is controlled by its product type (e.g., column, double-tee, slab). The control number at this phase is called a *product code.* In engineering and detailing, a precast concrete piece gains specific geometry. All precast concrete pieces with "similar" geometry are regarded as the same piece for production. The control number for similar pieces is called a *piece mark* in the North American precast concrete industry. Similar pieces are usually identified by the overall shapes of precast concrete pieces. But each company has slightly different identification rules depending on its production methods or practice. Subtle differences (or variations) between similar pieces are denoted by qualifiers added to the end of pieces marks. A third numbering is the *production serial number*, which is unique for each piece of concrete produced. Scheduling of precast concrete piece production is a complex optimization process considering the erection schedule and production capacity utilization. Naturally, the production serial number (or piece mark) of a piece is different from the *erection sequence number* and the *inventory (location) number*, which depicts the location of a piece on a storage yard. Design, production, finishing, storage, shipping, erection, and management of them, are all areas that require deep understanding of precast concrete practices and optimization processes.

2.4 Connections

Another example of an intelligent precast design / engineering function we specified is parametric connections. In order to increase the productivity of precast concrete piece design and engineering, automation of connection design was considered essential. Parametric modeling systems should apply connections parametrically and maintain the geometric integrity of precast pieces in assemblies, and of the connections between them, by embedding the required behavior of pieces and connections in response to design or detailing changes. For example, application of a column to column splice should include generation of parametric parts as shown in Table 1.

However, providing thorough definitions of how precast pieces and connections should respond was a key challenge, because of the difficulty in describing dynamic effects in an unambiguous way using static drawings. As a shorthand for describing Building Object Behavior (BOB), the Georgia Tech team developed a notation, called the *BOB notation*. The BOB model for parametric connection design includes fields such as *connection name, version, author, data, primary (supporting) part, multiple secondary (supported) parts, planned use, known limitations/rules,* and *definitions & default values of parameters*.

There is no such thing as a generic connection between two parts. Only certain types of connections can be used depending on the geometric shapes and load conditions of connected parts. For example, the column-to-column splice with anchor bolts (C-C-AB) connection illustrated in Figure 2 can be used only between a rectangular column and rectangular column or between a rectangular column and a rectangular Cast-In-Place (CIP) footing.

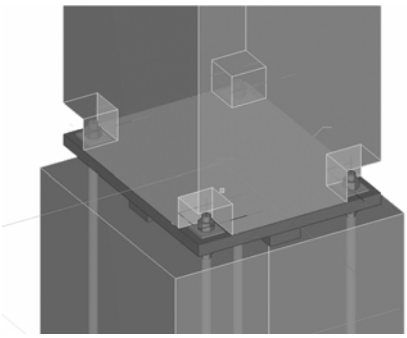

Figure 2 A column-to-column splice with anchor bolts connection (C-C-AB)

Table 1 Planned use and known limitations of a connection

Planned Use (Initial Goals for Functionality):
• Create a fitting between columns (Adjustable Grout Joint) • Create Base Plate (Adjustable Thickness, associative size with column & associative hole diameter with Base Plate) • Create 4 Shim packs (Adjustable size & offset from column face) • Create 4 Anchor Bolts (Adjustable size/projection/embedment and offset from column face) • Create Nuts & Washers (Adjustable sizes with associative hole diameters to Anchor Bolts) • Create Pockets (Associative to column face, adjustable offset to T/O Anchor Bolt and AB offset from Column face) • Create Grout Bed (to track volume)

Known Limitations/Rules:
• Can only be used with square or rect. columns. (no rounded surfaces) • Main / Secondary column faces should be parallel (non-aligned columns must be visually checked & adjusted to suit) • Can only be used with square or rect. columns. (no rounded surfaces) • Main / Secondary column faces should be parallel (non-aligned columns must be visually checked & adjusted to suit) • Bottom (Main) object must be equal to or larger than Top (Secondary) object • Base plate cannot be created wider than column

A large set of basic precast connections was collected along with examples of them. Most of these were implemented as parametric connections by technical committee members and shared using the website. Some of the basic connections modeled include:

- Double Tee to Flange Connection
- Double Tee to Cast-In-Place Ramp Connection
- Spandrel/Wall Continuous Footing Connection
- Spandrel to Steel Column Tie Back Connection
- Double Tee Solid Wall Connection
- Inverted Tee to Column Connection
- Spandrel Column (load bearing) Connection

In practice, the parametric object planner and the BOB notation were employed only in some cases through the requirements specification phase and the parametric connection implementation phase. We identified several limitations. There was no mechanism and application to directly transform the specified building object behavior in the notation into real parametric object. Therefore, as users became more proficient at implementing and editing parametric connections directly in the software, full specification of building object behavior became a cumbersome and additional task. However, the need for explicit descriptions of expected/implemented building object behaviors was underlined by copious e-mail communication between PCSC members in the process of sharing developed parametric objects among them. Parametric objects without good descriptions of the intended behaviors are like computer-implemented functions without good documentation. As parametric modeling tools become more prevalent, an efficient method to explicitly and unambiguously describe the design intentions will be crucial.

2.5 Building Assemblies

Some building components can be controlled much more efficiently as an assembly than as an individual piece. For example, a stairwell and an elevator shaft often pierce through several stories. If the location of a stairwell changes, the holes, which penetrate through several floors should be moved together and the locations of attached connections should be adjusted.

In precast, the act of dividing the façade of a building into a production-optimized, yet aesthetically pleasing, shape is called *panelization*. Each façade piece will be manufactured individually. However, in the design phase, users should be able to edit the façade as a whole if they wish. Later, joints and connections can be added along the panelization grids in order to divide a façade into individual pieces.

These are only a small number of examples of building assemblies. Another example includes a floor assembly, washes, and toppings.

2.6 Drawings and Reports

Drawings are often accused of being an ambiguous form of representation, but are indeed a succinct

summary of complex geometry. They are an effective communication medium between different parties for some tasks. Drawings cannot be fully automatically generated by a system because each company has different conventions for abstracting and simplifying certain things and also because each project has its own dimensioning requirements.
Automated report generation (e.g., bill of materials) is another complex issue. Each company has different ways of calculating surface areas and volumes of pieces depending on product types and other detailed estimation rules: e.g., whether to ignore or count small holes and reveals.
The PCSC members collected hundreds of drawings and reports and analyzed required representation types and data fields for the precast concrete industry through the detailed specification process.

2.7 Automated Rebar Design and Embeds

There are three major building codes (i.e., IBC, BOCA, and UBC) used in the US, as well as regional building codes. Canada has its own building code and also many regional codes. The US uses the imperial measurement and Canada uses the metric system. Thus, standard rebar, strands and meshes are different, and the details are different. Various examples and standards were collected and categorized through the specification process.

2.8 Other Functions

The items and details listed in this paper are only the tip of the iceberg. The technical specification developed covers short-term issues such as user-interface improvement issues and long-term development issues such as the Precast Concrete Product Model (PCPM) implementation for data exchange between different applications.

3. PROJECT GHOSTING

Three beta versions of a new product, named *Tekla Structures*®, have been developed and released for the PCSC members to review. The PCSC member companies "ghosted" (i.e. reproduced) real projects using the beta versions in parallel to the production of precast concrete using traditional 2D drafting systems. The purpose was to identify functionality gaps possibly missed in the specification process. Figure 3 illustrates an example of a parking garage modeled by David Mahaffy at Strescon Ltd.

Figure 3 Queen Elizabeth II Health Sciences Center Parkade, Halifax, Nova Scotia

Initial improvements in engineering productivity have been assessed. Modeling of full building structures, including their connections, and producing general arrangement drawings, could be accomplished in less than half the time using the prototype 3D CAD system than could be achieved when using traditional 2D drafting systems. Table 2 shows the work rates by project size. Table 3 shows how the project sizes were defined. Detailed information on the results is available in [1]. Note that this does not include rebar detailing and other functions, which have not been delivered yet.

Table 2 Comparison of Engineering Productivity

Project Size	2D Drafting (hours per 1,000m^2)	3D CAD (hours per 1,000m^2)
Medium	52.5 hours	2.3 - 5.9 hours
Small	171.5 hours	5.7 hours

Table 3 The Project Sizes

Project Type	Size Measure	Small	Medium
Architectural	Façade area (m^2)	≤ 1,000	1,001–10,000
	Piece Count	≤ 100	101–750
Structural	Floor area (m^2)	≤ 7,500	7,501– 30,000
	Piece Count	≤ 250	251–1,000

4. DISCUSSION

There have been many past efforts to automate certain aspects of precast concrete design, engineering, and production. But the PCSC project is the first industry-wide attempt to develop an integrated design and engineering 3D CAD system for the North American precast concrete industry. The PCSC project involves a unique collaboration between an industry sector (i.e., the precast concrete sector), academia, and a major CAD vendor specializing in Architecture, Engineering, and

Construction (AEC). The key success factors can be summarized as follows [8]:

- effective leadership within the precast industry,
- careful planning with proactive teams,
- project coordinators/facilitators that can lead the direction and the scope of the project towards realizable goals (e.g., Georgia Tech)
- fear of progress made by competing sectors (e.g., the steel construction sector)
- clear and reliable economic impact assessment [9-11]
- early initial consensus regarding the potential of 3D modeling replacing 2D drafting
- identification of a suitable 3D parametric platform

Some may argue that the success of this project may be due to the fact that the precast concrete sector is more manufacturing-oriented than other traditional sectors in AEC. It is partially true that only a few manufacturing-oriented sectors (e.g., the steel construction sector, the kitchen cabinet sector, and the staircase sector) in AEC have been very successful in adopting new technologies. However, in contradiction to common perception, the precast concrete sector is much closer to the traditional AEC sectors than to the manufacturing industry. Precast concrete pieces generally cannot be mass-produced and are unique by project. Thus, the success of this project suggests the potential of applying similar technology to broader AEC sectors.

Design systems with the capability to store and manage such complex design and engineering information are called *Building Information Modeling* (BIM) systems. However, we only have the outlines of BIM. There is much work to be done by academia and industries to turn the BIM technology into a practical solution for different sectors of the construction industry.

Acknowledgments

The authors cordially thank the PCSC members and Tekla developers for their devotion to this project.

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MULTI-CRITERIA OPTIMIZATION OF UP-TO-DATE CONSTRUCTION TECHNOLOGY

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ABSTRACT: The article analyzes the methods of multi-criteria alternative technological solution evaluation in construction environment. Methodology, which is used, allows to complexically evaluate the efficiency of construction designed decisions at the stage of preparation phase. There has been done a practical technological modeling of installation process of concrete floor as well as there have been determined optimal solutions. In order to achieve the results mentioned, a method of proximity to an ideal point was used.

KEYWORDS: multi-criteria optimization, method of proximity to an ideal point, rational trusses.

1. INTRODUCTION

At the very moment in Lithuania and other countries various construction and projection firms offer to use all kinds of new technologies and its systems, structural decisions, proper materials used as well as work implementation methods, without paying any attention to the factors, effecting the choice of selecting the most effective technology of construction process. Having in mind that funds should be realized rationally, it is the matter of vital importance to measure the practical adaptability of technologies being used either they are new or have been used for many years to achieve the best technological decisions. In order to achieve the efficiency of the funds invested and diminishing construction duration as well as increasing its quality, various construction process technologies are developed and improved by using modern technical and informational tools, which are integrated into the stages of projection and construction. The prospective technological processes' decisions and operations, their efficiency and competitiveness are programmed at the stage of construction objects' projection. In order to achieve the efficiency of construction technology it is advisable to use the achievements of fundamentals and applied science to solve the main tasks in various spheres of construction decision modeling and optimization.

While modeling and projecting construction technologies, it is advisable to perform the multi-criteria analysis of technological processes and decisions on the grounds to fully coordinate the goals of the interested parties (customer, projector, and contractor). That is why major principles and methods of construction decision technology multi-criteria optimization as well as questions associated with alternative decision technologies and mathematical modeling are analyzed in this paper. As for example, which provides the practical technological modeling of installation process of concrete floor and determining the optimal decisions based on the method of proximity to an ideal point.

2. MAJOR PRINCIPLES OF CONSTRUCTION TECHNOLOGICAL DECISION OPTIMIZATION

Applicable technological and other project decision optimization methods used in projection and construction processes could be divided into two major groups: applied mathematics and systemic-technical analysis methods. A great deal of construction organization tasks could be solved by using mathematic statistics (correlation and regression analysis), theory of chances, mathematic programming, 'gambling' theory, multi-criteria optimization and other methods. The selection of optimization method depends on the task character which is solved, the possessed source information and frequently it requires local interpretation. While solving practical construction optimization tasks, most frequently only one (the most important) of several economic criteria is chosen (ex.: total construction price, object construction or separate pieces of construction per one solid meter ($1m^3$) price, the revenue received, the greatest turnover, etc.). The significance of the criterion selected is very important. It shows that one of the criterions mentioned (for example, revenue received), which is selected by the interested party, is much more important than the other one, for example, total construction price. So to be concrete it shows the significance of one criterion to the interested party in comparison to the rest, which are left as less significant or insignificant. The significance of the

criterion could be determined by employing statistical, expert opinion based methods, even comparison, and entropy methods. These methods help to determine various theoretical, subjective, and complex values of great significance that are further used in the decision optimization counting processes. By counting values it is meant that the interested party could choose the criterion (they think) of the greatest significance. Moreover, the client is frequently much more interested not in the price, but in other criteria like construction duration, aesthetics, harmfulness to the health of the materials used, longevity, convenience to exploit, comfortability, etc. So any construction technological decisions could be described and optimized according to the following system of criteria evaluation, where the criteria could be expressed by the indices of technological economy (TCI) and quality characteristics (QC). For this purpose methods of multi-criteria decisions are used [1, 2].

We can definitely state that each of the decision optimization method mentioned has got its own advantages and disadvantages. Moreover, each of them could be used to solve the tasks of specific constructions groups. They help to create various optimization models of theoretical objects, technological or work processes like technological net models (alternative decisions, resources, dynamic, duration), mathematic models (shape of matrices, equation systems, various probability models), expert level systems, decision support systems and many others models.

Researches of modeling and optimization were founded on the basis of applied mathematics method, economics, system theory, cybernetics, and in the sphere of counting technological science and its integration. While optimizing technological construction processes, it is advisable to apply the theoretical principles of system methodology on the grounds that in nowadays the technological projection methods which are used do not correspond to the requirements of effective decision making. It could be noted that one of the major disadvantages are the decisions are accepted synonimically, without any preliminary examination and evaluation of the model of construction process technology and many the like multi-criteria evaluation [3]. While solving the any technological decision optimization problem, it is necessary to perform 3 major steps of construction process systemic examination (Figure 1). While modeling the construction composite process technological decisions, it is advisable to accept these main preconditions [4, 5]:

- All possible variations of complex process technologic decisions have to be constructed. Moreover, technological connections and partial variants of the processes (partial alternative decisions) have to be established.
- While forming the net model, consisting of partial process technological variants, it is necessary to take a precondition that only one of many other partial process technological variants will be implemented.
- Every partial process has got its individual time duration, which is either technologically based or depends on the work expenditure.

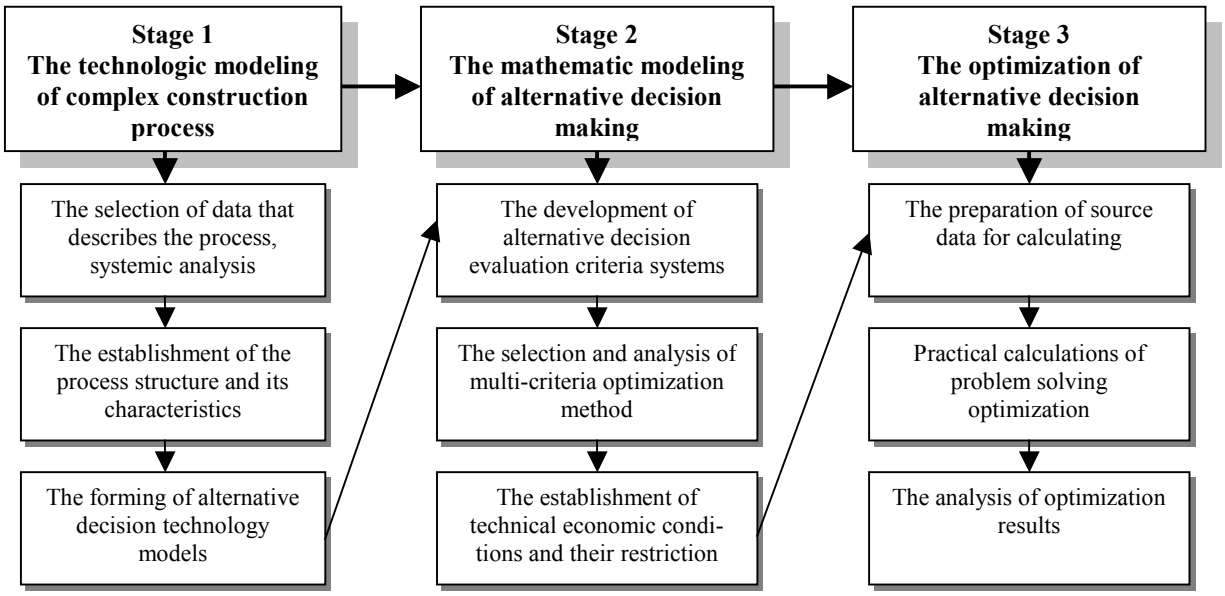

Figure 1. The steps of construction composite process systemic examination

So while creating the mathematical model of alternative technological decision making, it is advisable to define the set of the compared alternative decisions and their evaluation criteria. In that case, the source data matrix P, presented in Table 1, is prepared.

Table 1. The source data matrix P

Alternative decisions	Evaluation criteria			
	K_1	K_2	…	K_n
a_1	X_{11}	X_{12}	…	X_{1n}
a_2	X_{21}	X_{22}	…	X_{2n}
…	…	…	…	…
a_m	X_{m1}	X_{m2}	…	X_{mn}

The source data matrix P most often consists of different units of measurement. That is why the matrix should be normalized, i.e. it has to be transformed into the anti-dimensioned unit or sizes. Knowing the aims of the solution as well as applying the methods of normalization various normalized values of indices are obtained, which play the key role in other stages of solution multi-criteria optimization.

3. THE MAJOR RUDIMENTS OF APPLYING THE METHOD OF PROXIMITY TO AN IDEAL POINT, USED TO EVALUATE THE TECHNOLOGY

The main essence of the multi-criteria evaluation method is formation of generalized composed criterion. It is based on the comparison deviation of the criteria from so called the ideal criteria, consisting of the best variant criteria being analyzed. By applying the method and K_{bit} criteria, it is advisable to take into account that each variant of the task problem solving utility function has got the tendency to monotonously increase or monotonously decrease i.e. the larger value of any indices, the better it is or worse for less of the same index value. It depends on the fact whether the utility function increases or decreases. Indices have to be either cardinal or ordinal. If we have got the ordinal (qualitative) indices, they should be quantified. Besides, significance values should be determined, otherwise, they all are accepted as being equals. The application algorithm of the method of proximity to an ideal point, estimating the significance of the criteria, is presented in Figure 2.

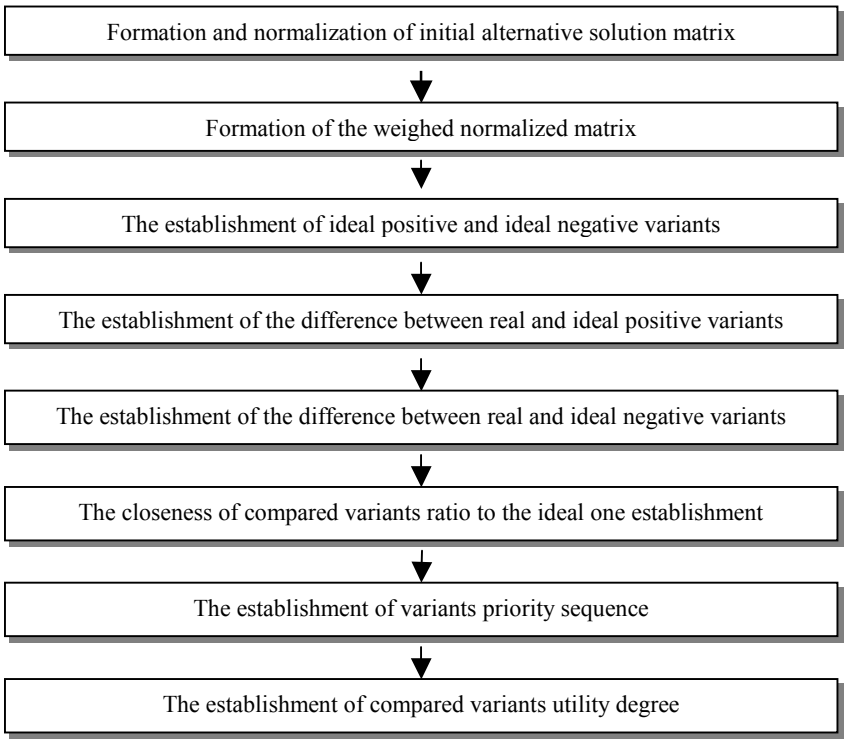

Figure 2. Application algorithm of the method of proximity to an ideal point

The matrix P of alternative architectural decisions is created. There could also be criteria either grouped or ungrouped. The matrix normalization is being dome according to the formula:

$$\overline{x_{ij}} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \text{ kur } i = \overline{1,m};\ j = \overline{1,n} \qquad (1)$$

If the significance of the subjective or theoretical ($\overline{q}$ or q_t) criteria is known, then the vector column multiplied by the normalized matrix corresponding column.

We get weighed matrix $\overline{P^*} = [\overline{P}] \cdot [q]$ (2)

If there are no values of significance, then $\overline{P} = \overline{P^*}$ ($\overline{P}$ matrix is compared to the weighed matrix), i.e. we take the precondition that entire alternative solution criteria are equally important. The ideal positive variant is being established:

$$a^+ = \left\{ \left[\left(\max_i f_{ij} / j \in I \right), \left(\min_j f_{ij} / j \in I' \right) \right] / i = \overline{1,m} \right\} = \left\{ f_1^+, f_2^+, ..., f_n^+ \right\} \quad (3)$$

where I – indices of ratio (maximizing), which possess the highest values.

The ideal negative variant is being established:

$$a^- = \left\{ \left[\left(\min_i f_{ij} / j \in I \right), \left(\max_j f_{ij} / j \in I' \right) \right] / i = \overline{1,m} \right\} = \left\{ f_1^-, f_2^-, ..., f_n^- \right\} \quad (4)$$

The difference (distance) between real and ideal positive variant is being found:

$$L_i^+ = \sqrt{\sum_{j=1}^{n} \left(f_{ij} - f_j^+ \right)^2} \quad (5)$$

where a_i – real variant; a^+ - ideal positive variant; L_i^+ - positive distance.

The difference between real and ideal negative variant is being found:

$$L_i^- = \sqrt{\sum_{j=1}^{n} \left(f_{ij} - f_j^- \right)^2} \quad (6)$$

$K_{bit,\ i}$ calculation of values (each alternative value is found):

$$K_{bit,i} = \frac{L_i^-}{L_i^+ + L_i^-}, \text{ when } \forall_i; i = \overline{1,m} \quad (7)$$

$0 \le K_{bit} \le 1$, besides,

$$K_{bit,i} = \begin{Bmatrix} 1, jei & a_i = a^+ \\ 0, jei & a_i = a^- \end{Bmatrix} \quad (8)$$

The best (the most rational) architectural solution will become the one, which K_{bit} value will be max ($K_{bit,i}$=max). Using the values we form the priority sequence. Utility degree establishment. We compare the value of the variant examined with the value of ideal variant.

$$N_i = \frac{K_{bit,i}}{K_{bit,\max}} \cdot 100\% \quad (9)$$

4. THE ESTABLISHMENT OF THE OPTIMAL FLOOR COVER EQUIPMENT TECHNOLOGY, APPLYING THE METHOD OF PROXIMITY TO AN IDEAL POINT

The change appeared in technological systems affect not only the rest systems parts or elements, but also the expected final result. That is why it is the matter of vital importance to deliver systemic structuralization of the construction technological processes.

The installation of the floor cover is only a partial installation process, which could be analyzed in the complex manner. The complex process of the floor cover equipment maximally can form 7 partial processes. Each partial process has got its own conventional sign, for example: P – preparation of cover; I – the establishment of the ironed coat; G – surface priming; D_1 – installation of first cover coat; D_2 – installation of the second cover coat; S – slushing of juncture; L – cover varnishment.

All possible combinations of cover floor are created (Figure 3).

Each partial process possesses the original structure, which is distinctive from the rest (Table 2). Besides, the processes of floor installation can differ in the performance of separate operations. They could be either mechanized or hand-held. Moreover, there could be difference in the manner of separate operation performance, equipment used to perform the process of installation, preparation for the work, the supply of materials and manufactured products, methods of quality control.

Technological floor cover installation model is established in the following stage, where the combination of complex processes are reflected as well as combinations of all possible partial processes and correlation between them. The best model, which is suited for the case is net model.

While establishing the combinations of partial processes, the technological combination sequence of partial processes is found. It is important to establish the combinations of technological connections among the separate partial processes, because it could happen so that the variant of the partial process does not possess the connectivity with the other variant of the partial process, i.e. one of them could have no technological connection with another.

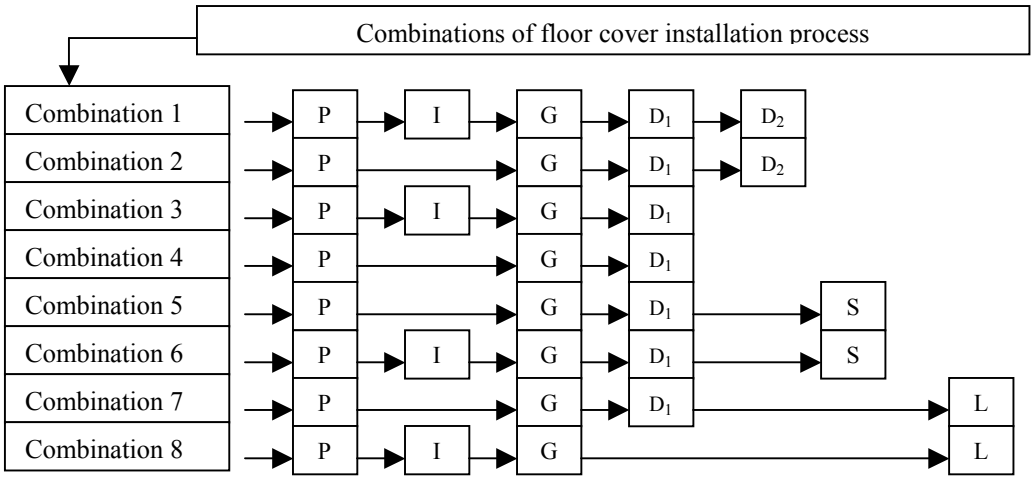

Figure 3. Combinational schemes of floor cover installation complex process

Table 2: Combinations of floor cover equipment partial processes

The code of partial process variant	The name of the floor cover equipment partial process; combinations of partial process (short description)
P	Surface preparation: - the take off of the cement pellicle, dust removal form the surface, corners making rounded, all arrangements
I1 I2	- the installation of the ironed cover from the cement grout - the installation of the ironed cover from the getting smooth grout (simple)
G G1	- carrying up of the primer, rubbing, surface thickening - carrying up of the primer for the basis of cement surface
$D_1$1 $D_1$2 $D_1$3 $D_1$4 $D_1$5	- the installation of one-layer primer from the mastic composition - the installation of two-layer primer from the mastic - the installation of primer layer while painting - the installation of the upper primer layer from tiles - installation of the upper primer layer from the grout on the basis of cement
$D_2$1	- the installation of the upper primer layer from mastic
S1 S2	- slushing of juncture among the tiles - slushing of cement surface
L	- priming of cover and varnishing (twice)

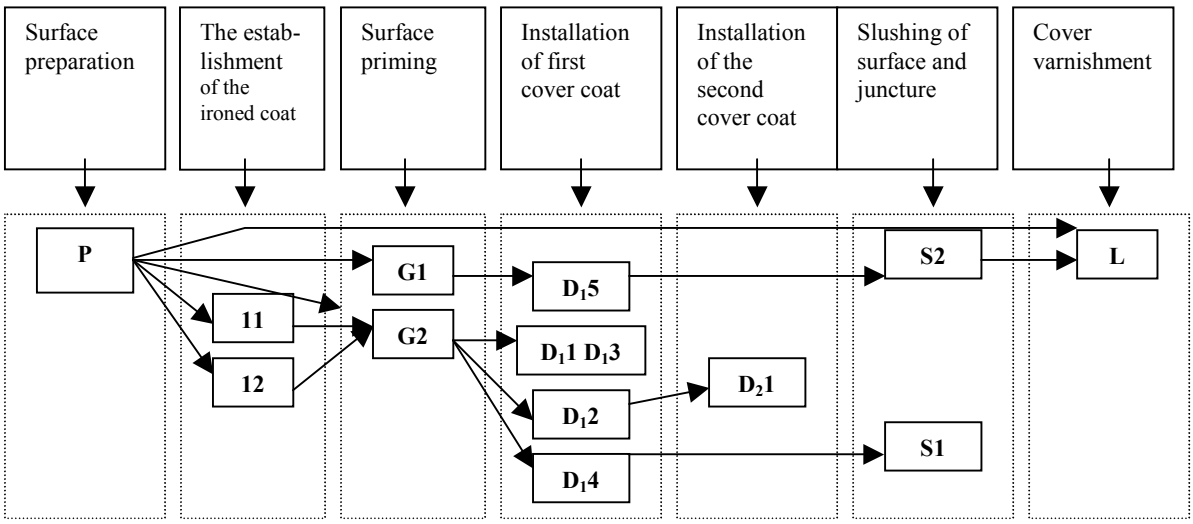

Figure 4. The scheme of variant technological connections between the separate partial processes

According to the data presented in Table 2 and Figure 4 as well as the construction methodology of net model, the net model of floor cover installation process technology is formed. The net model of floor cover installation process technology is the major scheme on which variants of the complex processes are selected and furthermore the continuous calculations of the variant values are performed. All possible ways from the beginning till the end are in search. Each possible way of the technologic net model possesses a different composition of partial processes. Entire possible ways of technologic model are presented in Table 3.

Table 3. Variants of floor installation complex process

Variant	Variant of complex process, defining	
	The way of technologic way model	Combination of partial processes variants
1	1→2→6→8→10→12	P→G→$D_1$1
2	1→2→6→8→10→13 →17→20	P→G→$D_1$2→ $D_2$1
… 14	1→2→3→5→6→8 →10→15→18→21	P→12→G→$D_1$4→ S1

In order to select the most suitable variant of floor cover installation the evaluation system is formed (Table 4).

Table 4.Evaluation criteria system

No.	The name of criterion	The description of criteria
1	The price of floor installation variant	It is the summed price of materials, mechanisms and work costs, meeting 1m^2 of the floor's cover
2	Work costs	It shows the workforce working time per hour, needed for the installment of 1m^2 of the floor
3	The level of work mechanization in percentage (%)	It shows the relative accumulated workforces' mechanized work costs, expressed in percentage
4	The floors' resistance to wear and tear	The index shows how many grams are polished within 1cm^2, while performing tests according to Taber, who directly evaluates the longitude of the cover
5	Chemical resistance of the floor cover (in points)	The resistance of the floor cover is tested in various aggressive conditions
6	The beginning of using the floor cover, in days	It estimates the duration of cover installation, which allows then the maximum loading of mechanism as well as chemical (work costs plus technological intervals / breaks)
7	Ecology conditions, in points	They reveal the harmfulness of the floor cover materials to the environment
8	Comfortability, in points	The index shows the satisfaction of working force while using the cover
9	Hygiene, in points	The index evaluates the hygiene characteristics of the cover while using it
10	Aesthetic view, in points	The index evaluates the appearance of the cover

Table 5. The calculation of criteria significance determination by the even comparison method

Criteria of matrix A

Criteria	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	ΣA_k	q	%
K1		2	2	1	0	1	1	1	1	1	10	0,11	11
K2	0		1	0	0	1	1	1	2	2	8	0,09	9
K3	0	1		0	0	1	0	1	1	1	5	0,05	5
K4	1	2	2		1	2	1	1	1	2	13	0,14	14
K5	2	2	2	1		2	2	1	2	1	15	0,17	17
K6	1	1	1	0	0		1	0	1	1	6	0,07	7
K7	1	1	2	1	0	1		1	1	1	9	0,10	10
K8	1	1	1	1	1	2	1		0	1	9	0,10	10
K9	1	0	1	1	0	1	1	2		1	8	0,09	9
K10	1	0	1	0	1	1	1	1	1		7	0,08	8
										Σ	90	1,00	100

The one of the major clients of floor cover projection, cover installation and exploitation processes is the customer. So while selecting the proper system of criteria evaluation, we first of all, should find out what needs and wants possesses the customer. The needs and wants lately are expressed by the criteria of evaluation. The investigation of customers' needs and wants is done. Biographical particulars were used to

perform the investigation. Some of the criteria are highly important to the contractor, who executes the whole work, as well as designers, who project floor cover for exploitation in some definite environment. Although not all of the criteria are equally important. That is why it is advisable to establish their significance.
Subjective criteria significance $\overline{q}$ is chosen in this paper, which was determined by the even comparison method (Table 5).

While performing the calculation of criteria significance on the basis of even comparison method, we received the significance of subjective criteria. The source matrix is formed in the following stage.
While performing the normalization of the matrix, and evaluating the significance of the criteria, as well as forming weighed normalized matrix, we received calculation results.

5. CONCLUSIONS

At the very moment in Lithuania and other countries various construction and projection firms offer to use all kinds of new technological projecting systems as well as work execution technologies, without paying any attention to the circumstances, affecting the choice of selecting the most effective technology of construction process.
In order to rationally employ the technological process of the funds, it is advisable to perform the modeling and multi-criteria evaluation of the alternative solution technology.
To perform the selection of the most suitable floor cover installation variant, the algorithm of solution optimization was formed a well as the criteria evaluation system, which describes the goals of interested parties striking for the aim in projection, work execution and exploitation processes.
While performing the investigated modeling and evaluation of concrete floor cover system alternative solution technology, was established that among all cover systems (epoxy, acrylic paint, tiles, cover on the cement basis) it is advisable to install the UREDUR 2000 covers in the aggressive environment.

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SENSORS AND SENSOR NETWORKS

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Abstract

Recently, sensing technology has been experiencing quantum leaps in price reduction and in performance. This has occurred because of simultaneous advances in new materials, cheap computing power, micro to nano-level integrated fabrication, wireless networking, and sophisticated information technology. At the same time, the pace of business and the pace of change have been accelerating and driving the need to be constantly and immediately aware in projects and business ventures of risks, threats, opportunities, and physical state. This need to be aware of the state of a project and the emerging capability to sense the state have come together to create a wealth of opportunities. Simply put, getting better information faster results in better decisions and competitive advantage. This paper explores how sensors, networked sensing systems, and tools to use sensor data in decision making will radically improve construction project performance over the next decade.

Introduction

- Background
  - Sensing technology advances
  - Industry challenges
  - Understanding that while sensors deliver objectivity, quantification, constant attention, ability to deploy anywhere, and save costs, human judgment is indispensable for targeting, deploying effectively, interpreting, and learning from sensor data
- Need
  - Complete awareness of project state to clear the fog
  - Learning from experience
  - Decision support; go to fact based, leadership driven
  - Data to calibrate life cycle economic models of facilities for investment portfolio planning and for asset management
- Opportunity to get better information faster so better decisions can be made at planning, management, and control levels
- Objectives of lecture to explore how sensors, networked sensing systems, and tools to use sensor data in decision making will radically improve construction project performance over the next decade, so that we can realize their potential impact and direct our advances
- Scope of lecture: primarily physical sensors; focus on procurement and construction phases but consider impact on all others; not exhaustive; no rigorous ontology or taxonomy
- Structure of lecture follows:

Project Data Needs

- All phases: planning, design, procurement, construction, start-up, operation, and decommissioning
- Types:
  - Business risk data: commodities, markets, financials, etc.
  - Control data: cost, schedule, and productivity
  - Location and position data: of people, materials, machines, etc.
  - Process transitional states: of curing, compaction, etc.
  - Test results: (e.g. welds)
  - Facility condition data: erection state, as-built geometry, distress, deterioration, etc.
  - Facility performance data: over operating life

- Forms:
    - Numeric, textual, image, 2D and 3D temporal and spatial streams, CAD formats, etc.

Sensing Capabilities

- Modes:
    - LADAR
    - RFID
    - GPS
    - 2D digital imaging
    - single axis laser ranging
    - internal encoders
    - ultrasonic, inductive loops, heat, biological, web based, etc.
- Enabling technologies:
    - Micro-fabrication and integration, e.g. motes
    - Cheap computing power
    - Wireless communications
    - Ad hoc networks
    - Internet
    - Off-the-shelf signal processing tools
    - Sensor stream databases
    - Knowledge management and data mining methods

High Potential Sensing Applications in Construction

- Concrete corrosion, maturity, strain, etc.
- RFID and GPS for materials management
- Laser positioning and GPS for machine control
- Internal encoders, RFID, and GPS for effortless productivity tracking
- Laser ranging, flash LADAR, and RFID for safety
- LADAR for as-builts

Research Issues

- Manufacture of cheap, robust, site deployable, standardized, “plug and play” sensors
- Error modeling
- Design of wireless sensor networks for fault tolerance
- Sensor data fusion and integration methods and applications
- Sensor database system design
- Automated data mining and learning algorithms
- Project process redesign due to sensor data frequency, volume, etc.
- Integration of sensing systems into construction project management systems

Business Issues

- business models for shared new technology investment or use risk
- corporate data security risks associated with wireless transmission of data
- impact of detailed data records on disputes, claims, litigation, etc.

Conclusions

- potential to reduce project duration by 50%, to reduce costs substantially, to improve safety, and to improve quality
- potential to improve predictability of life cycle performance
- some sensing technologies are ready for use
- more research in this area will pay off substantially

3D VISION TECHNIQUES AND APPLICATIONS TO PHOTO-REALISTIC SCENE RECONSTRUCTION

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Abstract: We present some novel concepts for the scene geometry recovery by a multi-camera system. A new global appearance measure is introduced for a novel generalized scene recovery methodology, called "the appearance-cloning."

For the efficient calibration of the multi-camera system, we investigate the projective properties of the concentric circle pattern. Specifically, two algebraic constraints from concentric circles are defined to calibrate the intrinsic parameters of the multi-camera system. Through a variety of scene reconstruction experiments, we demonstrate that the use of concentric circles greatly simplifies the calibration problem for the photo-realistic recovery of dynamic 3D scene.

Keywords: photorealistic 3D reconstruction, volume based approach, camera calibration

1. INTRODUCTION

Recent advances in image-based rendering approaches (view morphing, light field rendering) make it possible generate a photo-realistic novel view only from photographed images without scene geometry information [1-5]. Many applications, however, still require the correct scene geometry information in image based modeling and rendering (IBMR).

Computer vision techniques to extract the geometric information of real-world scene for IBMR can be categorized according to the sensing technology into either the active or passive sensing approaches.

Active sensing technologies (e.g., optical, laser, and time-of-flight range finder) normally provide high accuracy and good quality of 3D measurements. Many commercial solutions have been widely applied to various IBMR systems that use the scene geometry information. However, in most cases, the geometry information acquired from the active sensing technology should be combined with photographs for the photo-realistic 3D model generation and rendering. Moreover, the 3D scanner is still very expensive for the general consumers compared with the passive sensors such as a digital camera and cam-coder.

On the other hand, the passive sensing technology directly recovers the scene geometry information from a set of photographs, so no additional sensor is needed for IBMR. Moreover, digital cameras are available at a reasonable price. Therefore, 3D scene recovery by the passive sensing technology has attracted a great deal of attentions during the last several decades, and many elegant methodologies have been introduced and demonstrated those viabilities at each specialized application area and conditions. However, those methodologies are still hard to be a solution for our generalized scene recovery problem because of many hard-to-set ad hoc factors such as scene dependent control parameters, assumptions, and constraints [6-15]

For a methodology to be a practical solution for the generalized scene recovery problem, it should not rely on any ad hoc parameters to be set.

In this paper, we introduce a novel "global appearance measure" instead of local measures, and then propose a novel methodology, called "the appearance-cloning", as a solution to the generalized scene recovery problem.

For the scene recovery by a multi-camera system, an effective camera calibration method is necessary to deal with the partial views of calibration pattern by the multi-camera system. We develop a novel calibration pattern of concentric circles that can be extracted even with small partial view of the circle pattern. A two-step camera calibration method estimates the intrinsic camera parameters and the camera pose parameters. The proposed constraint properties of concentric circle patterns have concrete physical meanings, such as the position of the projected circle center and the projected radius-0 imaginary circle. Based on the constraints of the concentric circles, the intrinsic parameter is estimated from the image of the concentric circles without any assumption about a camera with three or more views.

2. APPEARANCE CLONING

Since the recovery of real-world scene from a set of photographs is generally ill-posed problem [6], the best that we can recover from photographs is the maximal photo-consistent 3D model that is re-projected into all the original photographs and reproduces those photographs [7]. Many previous researches have tried to find this maximal photo-consistent 3D model from photographs, and recent several volumetric approaches have introduced

promising methodologies by representing the recovered shape information in a common volumetric space defined by user.

The use of this common 3D space elegantly solves the view-dependent self-occlusion problem of arbitrarily-shaped scene, and makes the traditional "correspondence search problem" in 2D image spaces to be reformulated as the "occupancy decision problem" of each 3D primitive in the volumetric space by using the normalized cross-correlation measure of oriented 3D patch on a grid point [8] or the photo-consistency measure in a voxel [9].

Now, how can we recover the photo-consistent 3D model by using a global appearance measure? As shown in Figure 1, the global appearance measure is the photograph itself that is projected from the real-world scene to a known camera viewpoint. We can make the equivalent system in the digital domain in which we can control full operations. We first define a candidate 3D model in our digital domain, and then render this model to the known camera viewpoints. Through this process, we can get another global appearance which is composed of view-dependent appearances of candidate 3D model and has one-to-one correspondence with the given global appearance.

Then, we can get the photo-consistency of candidate 3D model about given photographs by directly comparing the appearance similarity between the given appearances and recovered appearances. And then, we can control our 3D model by using the appearance similarity error because we exactly know the relationship between the recovered appearance and our 3D model. Through these iterative operations, we can find the optimal photo-consistent 3D model by cloning the global appearance of given photographs. We call this methodology as "the appearance-cloning." If our equivalent system can correctly resemble the actual projection relationship from the real-world scene to each camera viewpoint and enough appearances are given to us, then the recovered 3D model can perfectly regenerate given photographs and can be a photo-consistent clone of the real-world scene according to the chain-rule.

2.1 Modeling of digital 3D model space

To represent the real-world scene in our digital domain, we use the voxel as a basic primitive. We define the voxel as a single-colored opaque cubic volume. Consequently, the state of each voxel can be either opaque or transparent in the voxel space.

Now, define a voxel space $\mathcal{V} \in \Re^3$ that encloses the scene with a comfortable margin and is composed of (L,H,W) voxels. Since we define the voxel as a cubical volume, each voxel $v \in \mathcal{V}$ projects to several pixels per visible camera (i.e., follows the volume-projection). Then, the scene can be approximately represented as a combination of opaque and colored surface voxels. Let such a combination of opaque surface voxels be a candidate 3D model $\mathcal{S}$. Then, there are $2^{L\times H\times W}$ candidate 3D models. The optimal photo-consistent 3D model $\mathcal{S}^*$ that we want to find is one of those candidate 3D models. Let $2^{\mathcal{V}}$ be the set of those candidate 3D models. Then, $\mathcal{S}^* \in 2^{\mathcal{V}}$. We call $2^{\mathcal{V}}$ digital 3D model space.

These complete candidate 3D models can be rendered to each camera viewpoint, which is used to capture given appearance, and then we can get the recovered appearances from those candidate 3D models.

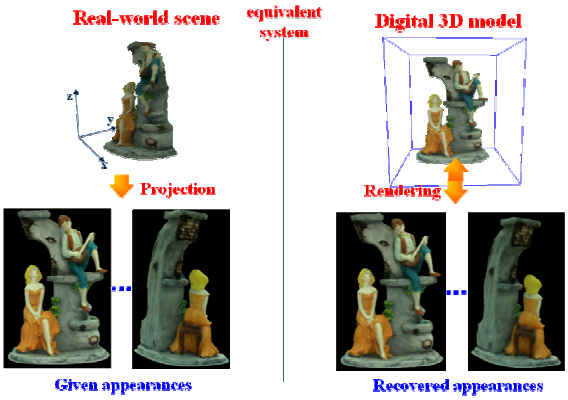

Figure 1. Appearance cloning: Left) the real-world projection relationship. Right) the equivalent digital-world rendering relationship.

2.2 Appearance similarity measure

Now, we can directly compare the appearance similarity between given appearances and recovered appearances. However, in most of scene recovery from multi-view images, the real-world scene is not observed in whole image region. We adopt the region of interest (ROI) to exclude those projected regions of uninteresting scenes. If our interesting scene is a single real-world object, ROI of each image is exactly the same with the inside silhouette region of projected object. However, since we can directly recover multiple real-world objects or landscape, we use the notion of ROI rather than silhouette. In actual scene recovery, this ROI can be automatically extracted by using the blue screen technique, or manually extracted by using a tool like the intelligent scissor [16] or its variants.

From now on, suppose that the ROI information of the given input images is known as a prior knowledge. Before defining appearance similarity measure of a candidate 3D model, we use several notations. Let $\mathcal{I}$ be the given appearances within ROI of input photographs and $\mathcal{R}(\mathcal{S})$ be the one-to-one corresponding recovered appearances rendered from a candidate 3D model $\mathcal{S}$. Let $\mathcal{P}$ be the set of all ROI pixels in the given input photographs. Then, we can derive the uniqueness constraint from the ROI information of input photographs:

[Uniqueness constraint]

If a candidate 3D model $\mathcal{S}$ is to be a candidate of photo-consistent 3D model, every pixel $p \in \mathcal{P}$ on the recovered appearances $\mathcal{R}(\mathcal{S})$ must have its own occupying voxel $v \in \mathcal{S}$ and each surface voxel $v \in \mathcal{S}$ should not project to the outside of ROI at any camera viewpoint.

This uniqueness constraint greatly reduces the number of meaningful candidate 3D models in our 3D model space $2^{\mathcal{V}}$. Let $2^{\mathcal{CV}}$ be the set of candidate 3D models satisfying the uniqueness constraint. Then, $2^{\mathcal{CV}} \subset 2^{\mathcal{V}}$ and $\mathcal{S}^* \in 2^{\mathcal{CV}}$. From now on, we consider a candidate 3D model $\mathcal{S} \in 2^{\mathcal{CV}}$, except where noted.

To define the appearance similarity measure $\Pr(\mathcal{S} \mid \mathcal{I})$ of a candidate 3D model $\mathcal{S}$, we use the Bayes' theorem

$$\Pr(\mathcal{S} \mid \mathcal{I}) = \frac{\Pr(\mathcal{I} \mid \mathcal{S}) \Pr(\mathcal{S})}{\sum_{\mathcal{S}^k \in 2^{\mathcal{CVH}}} \Pr(\mathcal{I} \mid \mathcal{S}^k) \Pr(\mathcal{S}^k)}. \quad (1)$$

Here, if the prior probability is uniform for all candidate shapes, then $\Pr(\mathcal{S} \mid \mathcal{I}) \propto \Pr(\mathcal{I} \mid \mathcal{S})$.

Let $\mathbf{c}_I(p)$ be the pixel color of given appearance image at a pixel $p \in \mathcal{P}$ and $\mathbf{c}_R(p \mid \mathcal{S})$ be the pixel color of corresponding recovered appearance image under the candidate 3D model $\mathcal{S}$. Then, the appearance similarity measure of a candidate 3D model $\mathcal{S}$ can be defined as

$$\Pr(\mathcal{I} \mid \mathcal{S}) = \prod_{p \in \mathcal{P}} p\left[\mathbf{c}_I(p),\ \mathbf{c}_R(p \mid \mathcal{S}) \mid \boldsymbol{\theta}\right] \quad (2)$$

where $p[\circ \mid \boldsymbol{\theta}]$ is a probability model of each pixel $p \in \mathcal{P}$, which has a control parameter vector $\boldsymbol{\theta}$, that returns the reliability of $\mathbf{c}_R(p \mid \mathcal{S})$ about $\mathbf{c}_I(p)$.

Now, the remainder for the appearance similarity measure is how to define $p[\circ \mid \boldsymbol{\theta}]$. Although we have to use the probability model because of volumetric approximation of scene surface, we can inversely use the properties of volume-projection to model $p[\circ \mid \boldsymbol{\theta}]$.

2.3 Per-pixel statistical modeling

Since $\mathbf{c}_I(p)$ is given as an evidence, we have to model the probabilistic characteristics of $\mathbf{c}_R(p \mid \mathcal{S})$ in $p[\circ \mid \boldsymbol{\theta}]$. In practice, $\mathbf{c}_R(p \mid \mathcal{S})$ is the color of which a voxel ($v \in \mathcal{S}$) occupy that pixel ($p \in \mathcal{P}$). Therefore, $\mathbf{c}_R(p \mid \mathcal{S})$ is the function of candidate 3D model and we cannot directly estimate its characteristics in the 3D model space. On the other hand, if we approach inversely from the image space, we can estimate its characteristics from the physical volume-projection relationship between a pixel and its occupying voxels.

The evidence that is given to use is only the view-dependent appearances of real-world scene. Fortunately, we have a solution, which can estimate candidate $\mathbf{c}_R(p \mid \mathcal{S})$ (i.e., voxel color) from neighborhood color information centered on each pixel $p \in \mathcal{P}$, by using the physical volume-projection relationship.

To derive per-pixel probability model, we use the Euclidean color distance as a color similarity measure

$$x(p \mid \mathcal{S}) = \left\| \mathbf{c}_R(p \mid \mathcal{S}) - \mathbf{c}_I(p) \right\| \quad (3)$$

and assume that the intensity difference of each color-channel follows the zero-mean Gaussian distribution.

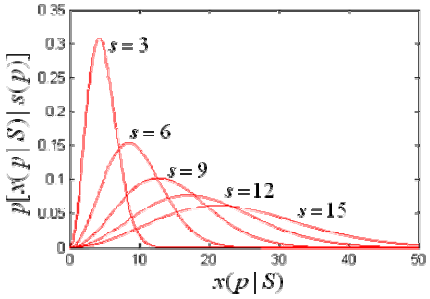

Figure 2. Maxwell distributions according the control parameter s

Then, the random variable $x(p \mid \mathcal{S})$ follows the Maxwell distribution [17]

$$p\left[x(p \mid \mathcal{S}) \mid s(p)\right] = \sqrt{\frac{2}{\pi}} \frac{x^2}{s^3} \exp\left(-\frac{x^2}{2s^2}\right) \quad (4)$$

where $x \in [0, \infty)$. $s(p)$ is the control parameter of Maxwell model.

In this Maxwell model, the control parameter $s(p)$ guides $x(p \mid \mathcal{S})$ to be the statistically optimal distance $\sqrt{2}s(p)$, and strongly constrains the allowable $x(p \mid \mathcal{S})$, as shown in Figure 2. Therefore, we can substitute this self-constrained per-pixel Maxwell model $p[x(p \mid \mathcal{S}) \mid s(p)]$ for $p[\circ \mid \boldsymbol{\theta}]$ in Eq. (3). Then we can get the reliability of recovered appearance color $\mathbf{c}_R(p \mid \mathcal{S})$ about $\mathbf{c}_I(p)$ from the per-pixel Maxwell model.

Now, we can estimate per-pixel Maxwell model for each pixel $p \in \mathcal{P}$ by fitting the control parameter $s(p)$ to the color statistics of candidate voxel colors.

Fortunately, the control parameter $s(p)$ of Maxwell model has following relationship with $x(p \mid \mathcal{S})$

$$s(p) = \frac{1}{2}\sqrt{\frac{\pi}{2}}E[x(p \mid \mathcal{S})] \quad (5)$$

where $E[x(p \mid \mathcal{S})]$ is the expectation of $x(p \mid \mathcal{S}) = \left\| \mathbf{c}_R(p \mid \mathcal{S}) - \mathbf{c}_I(p) \right\|$ centered on $\mathbf{c}_I(p)$.

Since we can substitute $\mathbf{c}_R(p \mid \mathcal{S})$ with our candidate voxel color, the per-pixel Maxwell model can be estimated with the closed-form solution. Let $\tilde{\mathbf{c}}(p)$ be the candidate voxel color that is estimated from two constraints of volume-projection. Then, we can estimate this $\tilde{\mathbf{c}}(p)$ with very simple shifted average footprint operation.

3. MULTI-CAMERA CALIBRATION USING CONCENTRIC CIRCLES

3.1 Algebraic constraints: rank deficiency

Without loss of generality, we can assume that the concentric circle center coincide with the origin of the world coordinate system. The circle Q is a diagonal matrix whose elements are [1,1,$-\rho^2$]. From these algebraic properties, we can derive some algebraic constraints of the projected concentric circle matrices.

Two ellipses from the same homography $\mathbf{P} = \mathbf{C}[\mathbf{r}_1 \quad \mathbf{r}_2 \quad \mathbf{T}]$ satisfy

$$\lambda_1 \mathbf{A}_1 = \mathbf{P}^{-\mathbf{T}}\mathbf{Q}_1\mathbf{P}^{-1}, \quad \lambda_2 \mathbf{A}_2 = \mathbf{P}^{-\mathbf{T}}\mathbf{Q}_2\mathbf{P}^{-1} \quad (6)$$

where $\mathbf{C}$ is a camera matrix and $\mathbf{r_n}$ is a rotation vector.

Taking the inverse on Eq (6) gives

$$\frac{1}{\lambda_1}(\mathbf{A}_1)^{-1} = \mathbf{P}(\mathbf{Q}_1)^{-1}\mathbf{P}^{\mathbf{T}}, \qquad \frac{1}{\lambda_2}(\mathbf{A}_2)^{-1} = \mathbf{P}(\mathbf{Q}_2)^{-1}\mathbf{P}^{\mathbf{T}} \quad (7)$$

The circle matrices $\mathbf{Q_1}$ and $\mathbf{Q_2}$ are simply diagonal as

$$\mathbf{Q_1} = diag(1,1,-\rho_1^2), \mathbf{Q_2} = diag(1,1,-\rho_2^2) \quad (8)$$

Their inverse matrices are

$$(\mathbf{Q_1})^{-1} = diag(1,1,-\frac{1}{\rho_1^2}), (\mathbf{Q_2})^{-1} = diag(1,1,-\frac{1}{\rho_2^2}) \quad (9)$$

Subtracting Eq. (9) from each other gives

$$\mathbf{A}_{\Delta}^{-1} \sim \mathbf{P}\mathbf{Q}_{\Delta}^{-1}\mathbf{P}^{\mathbf{T}} \quad (10)$$

where

$$\mathbf{A}_{\Delta}^{-1} \overset{\Delta}{=} (\mathbf{A_1})^{-1} - \frac{\lambda_1}{\lambda_2}(\mathbf{A_2})^{-1} = (\mathbf{A_1})^{-1} - \alpha(\mathbf{A_2})^{-1} \quad (11)$$

$$\mathbf{Q}_{\Delta}^{-1} \overset{\Delta}{=} (\mathbf{Q_1})^{-1} - (\mathbf{Q_2})^{-1} = diag\left(0,0,\frac{1}{\rho_2^2} - \frac{1}{\rho_1^2}\right) \quad (12)$$

From Eq. (12), the rank of both sides of Eq. (10) must be one.

We can rewrite Eq. (10) as

$$\mathbf{P}\mathbf{Q}_{\Delta}^{-1}\mathbf{P}^{\mathbf{T}} = \left(\frac{1}{\rho_2^2} - \frac{1}{\rho_1^2}\right)(\mathbf{CT})(\mathbf{CT})^{\mathbf{T}} \quad (11)$$

Because we assume that the concentric circle center is equal to the origin of the world coordinate system, $\mathbf{CT}$ describes the position of the projected circle center. The resulting homogeneous coordinate removes a scale factor relating to radii.

Moreover, the matrices of the imaged concentric circles have the other constraint – rank 2 constraint. This is because the circle matrices $\mathbf{Q_1}$ and $\mathbf{Q_2}$ have two repeated elements as in Eq. (9).

The rank-2 subtractive matrix of $\mathbf{Q_1}$ and $\mathbf{Q_2}$ is intuitively given by

$$\begin{aligned} \mathbf{Q}_{\Delta 2} &= (\rho_2^2 / \rho_1^2)\mathbf{Q_1} - \mathbf{Q_2} \\ &= diag(\rho_2^2 / \rho_1^2 - 1, \rho_2^2 / \rho_1^2 - 1, 0) \\ &\sim diag(1,1,0) \end{aligned} \quad (12)$$

This property holds if we assume the non-degenerate case of the projections. Once we find the suitable ratio of scale factor β, there exists the rank-2 subtractive matrix $\mathbf{A}_{\Delta 2}$ defined by

$$\mathbf{A}_{\Delta 2} \overset{\Delta}{=} \beta\mathbf{A_1} - \mathbf{A_2} \quad (13)$$

The resulting $\mathbf{A}_{\Delta 2}$ has an interesting physical meaning. Because of the homogeneity of the coordinates, the resulting matrix is expressed as

$$\mathbf{A}_{\Delta 2} \sim \mathbf{P}^{-\mathbf{T}} diag(1,1,0)\mathbf{P}^{-1} \quad (14)$$

From Eq. (14), $\mathbf{A}_{\Delta 2}$ is the projected imaginary circle whose radius is zero.

A final remaining problem is how to determine the relative scale factors α and β. There are various ways to determine them, and we suggest a method to find it by setting the scale factor with the generalized eigenvalues of $\mathbf{A_1}$ and $\mathbf{A_2}$ [18]. Due to the special form of the concentric circle matrices, the generalized eigenvalues must have two repeated ones and single distinct one. For rank one case, the repeated one is selected as a scale factor. Selecting single distinct one as a scale factor makes rank two subtractive matrix.

3.2 Intrinsic parameters from concentric circles

As described in [19], once the IAC is determined, the intrinsic parameters are obtained directly. Furthermore, the IAC can be estimated with six or more imaged circular points. In this section, we show that one set of the image of the concentric circles is sufficient to find a pair of imaged circular points.

The imaged circular points are on the vanishing line, as well as on the image of an imaginary conic whose radius is 0. The image of the radius-0 circle can be extracted up to scale factor using the rank-2 constraint. The projected imaginary conic is expressed as Eq. (14).

The vanishing line $\mathbf{l_p}$ extracted from a conic is

$$\mathbf{l_p} = \mathbf{A}\mathbf{x}_c \quad (15)$$

where $\mathbf{A}$ is the ellipse matrix and $\mathbf{x_c}$ is the projected circle centers [20].

In this case, the imaged circular points are the intersection of the projected radius-0 conic $\mathbf{A}_{\Delta 2}$ and the vanishing line of the plane $\mathbf{l_p}$.

The position of the projected circle center can be estimated from the algebraic rank-1 decomposition property.

However, comparing to the conventional point correspondence based algorithm, the proposed algorithm can estimate the intrinsic parameters only with partial views of concentric circles due to occlusion or limitation of field of view. Also, we don't need any kind of Euclidean measurements like lengths or even radii of the circles.

3.3 Experiments

The noise characteristic of the proposed calibration algorithm has been tested using synthetic data with respect to the numbers of views and the number of concentric circles. In practical case, the error is mainly caused by the quantization error of the edge points. The performance of this algorithm is analyzed under practical edge quantization noise that is in one pixel. The results are shown in Table 1. As expected, the performance of the proposed calibration algorithm improves as the numbers of views and circles increase.

Table 1. RMS error in focal length estimation (relative error) with edge quantization noise

	Error in αu (%)	Error in αv (%)
3 views with 2 circles (minimal case)	2.2952	1.5385
4 views with 2 circles	1.192	0.743
5 views with 2 circles	0.9264	0.5258
3 views with 3 circles	0.6514	0.3609
4 views with 3 circles	0.5064	0.3301
5 views with 3 circles	0.4427	0.2830

4. EXPERIMENTAL RESULTS

To show the practicality of the proposed algorithm, we applied it to multi-camera calibration. Figure 3 shows a camera setup, consisting of ten SONY DFW-V500 cameras, for the reconstruction of 3-D scene. In this case, the captured images suffer from FOV limitation. Figure 4 shows some captured images which are used for the calibration of intrinsic parameters. For camera calibration, we used nine images selected for each camera. Figures 5 and 6 show some of captured images and synthesized views from the 3-D reconstruction result using 'the appearance-cloning', respectively. Figure 5 shows one set of dynamic image sequences and full sequences can be reconstructed using the same framework.

Figure 7 shows some of 'Marble dataset' and their corresponding image and re-synthesized views using various reconstruction methods. To verify the accuracy of the reconstructed scene, the depth map is also shown. Note that the result from the proposed method is much similar to the ground truth.

Figure 8 shows one of 'Junglimsaji pagoda dataset' which are taken from one of Korean National Heritages by a digital hand-held camcoder. It shows that our optimization-based scene recovery can refine the scene geometry relatively well with pictures taken outdoor.

Figure 3. Multi-camera setup

Figure 4. Examples of images for calibration in multi-camera system

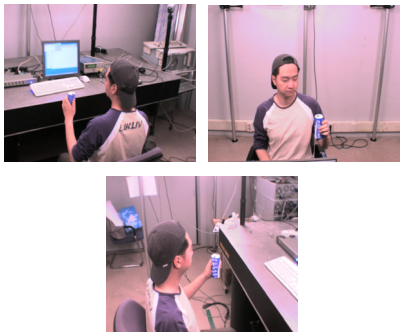

Figure 5. Examples of captured images

Figure 6. Examples of synthesized images

5. CONCLUSION

We have interpreted the photograph as a view-dependent appearance instead of combination of projected surface colors that is commonly adopted interpretation for the scene recovery. Based on this novel interpretation, we have introduced a new methodology, called "the appearance-cloning", in which we simulate the photographing mechanism of real world in our digital domain. Through our resembled mechanism, we can generate recovered appearances of our candidate 3D model that are one-

to-one corresponding to given appearances acquired from the real-world scene. Then, we have controlled our candidate 3D model by using our appearance similarity measure so that the recovered appearances resemble the given appearances.

For the practical implementation of multi-camera system, we propose a two-step camera calibration method using concentric circles. First, we calibrate each camera intrinsically, and the camera pose are subsequently estimated. The proposed constraint properties of concentric circles provide concrete physical meanings, such as the position of the projected circle center and the projected radius-0 imaginary circle. Based on the constraints of the concentric circles, we develop a new camera calibration algorithm.

We demonstrate that the photo-realistic scene reconstruction for indoor, outdoor and dynamic environments is feasible using some real-image sets by a multi-camera system or a single moving camera.

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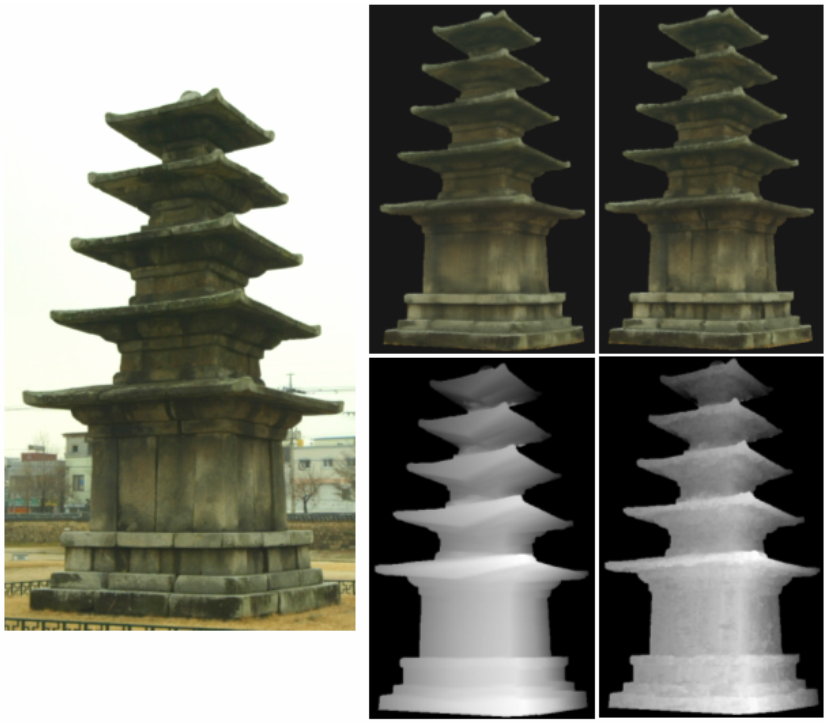
(a) (b) (c) (d) (e)

Figure 7 Qualitative comparison: First row shows the photometric recovery. Second row shows the geometric recovery. (a) Active 3D scanner. (b) Volume intersection (VI) - initial. (c) Probabilistic voxel Coloring (PVC) [14]. (d) Error optimization with the generalized voxel coloring (GVC/EO) [12]. (e) Appearance-cloning (Proposed).



(a) (b) (c)

Figure 8. Scene recovery of Junglimsaji Pagoda dataset: (a) shows two of input images. (b) shows the recovered appearance image and depth map of initial visual hull. (c) shows those of recovered optimal 3D model using our appearance-cloning algorithm.

FUTURE INNOVATIVE CONSTRUCTION TECHNOLOGIES: DIRECTIONS AND STRATEGIES TO INNOVATE CONSTRUCTION INDUSTRY

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Abstract:
The paper aims to discuss future direction of management of innovative technologies toward construction innovation. Our focus here is technology and knowledge fusions. At first technology and knowledge fusions in building construction are described. Secondary processes of technology and knowledge fusions are analyzed focusing on automation technology and information technology. Thirdly, a strategy to innovate construction industry is proposed from a viewpoint of technology and knowledge fusions. Finally, future directions and strategies of technology and knowledge fusions to develop future innovative construction technologies are to be presented.

Keywords: innovation construction fusion technology knowledge automation information management strategy

1 INTRODUCTION

The form of the building construction is different from the manufacturing industry, due to problems such as low productivity, many construction waste and materials, worker's accidents that are caused by the labor intensive works performed in job-site under built-to-order production supported by various typed of project participants.
To solve the problems, advanced technologies have been introduced from manufacturing industry with their concepts and methods to improve quality and productivity such as industrialization, prefabrication modularization, mechanization, automation and computerization.
Various types of advanced construction systems have been researched, developed and implemented in specific building projects to try to solve the problem of the low productivity by introducing advanced technologies such as prefabrication, automation and information technologies from manufacturing industry as well as concepts and methodologies associated with new technologies. The construction systems aimed to change styles of building construction to that of factory production through sophistications of developed technologies, methodologies and concepts.
Essentially construction firms present their engineering and management services at project level, appropriate approaches to innovate project-based firms based on efficient methodologies and clear strategies to perform technology developments are relevant. Our focus here is technology and knowledge fusions.
Technology fusion is an emerging methodology to integrate potential technologies among different disciplines, and it is also viewed as an effective approach to assisting construction firms respond to the difficult environment in which they are operating currently.
Knowledge fusion is also an emerging methodology to improve organizational knowledge creation ability that has been introduced to construction industry as by dynamically transform implicit knowledge and explicit knowledge of an organization.
To promote technology fusion, it is essential to have a structured way with clear goal, concept and strategy. Formerly Computer Integrated Construction (CIC) was regarded as a strategy to promote technology and knowledge fusions. CIC is an adaptation of Computer Integrated Manufacturing (CIM) to construction industry, and it is also viewed as an effective knowledge fusion driver, because manufacturing industry intended to innovate not only their production system but also their organizational knowledge management system by introducing CIM concept. To demonstrate the concept of CIC in construction industry, prototype systems were implemented to promote innovations in its process, organization and product through systematic technology development.
SMART system (Shimizu Manufacturing system by Advanced Robotics Technology) is a part of Shimizu's CIC strategy for developing an automated construction system, which automates a wide range of construction process of high-rise building by

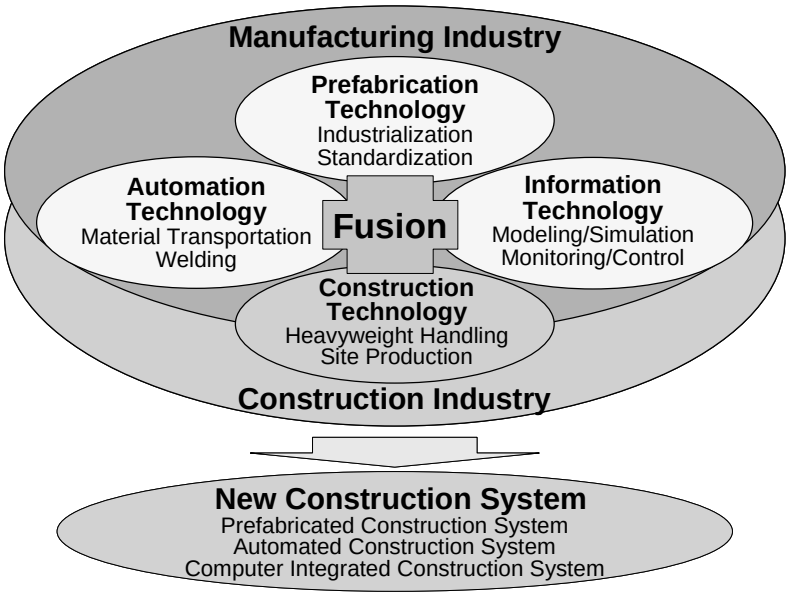

Figure 1. A Conceptual View of Technology and Knowledge Fusion for Construction Industry

integrating prefabrication, automation, and information technologies with construction technology. Also information management systems associated with an automated construction integrate a wide range of design, engineering, planning and management knowledge of the project functions.

By introducing SMART system, amount of labor required and the construction period are both reduced significantly, and the planning and management productivity is increased. However the originally developed SMART system is not applied since two construction projects at early development stage had been completed, the system have been improved and modified to several types of construction systems that are vital at present. Because technology development environment has been changed to focus more effective technology and knowledge fusions with other companies and industries.

Current challenging technology and knowledge fusions are mainly brought by comprehensive applications of IT systems. Major IT systems introduced to construction projects are well depend on 3D-CAD systems and networked communication systems, which is effectively applied to product design, production planning, real-time monitoring of construction process, control of transportation equipment in execution stage, and management of procurement and executions. By utilizing those IT systems, a remarkable progress has been made in the field of integrated management of process, organization and product of the project.

Future construction innovations will also depend on technology and knowledge fusions among different companies and industries. To promote technology and knowledge fusions, systematic and organizational promotion of technology development to be adaptable to needs and technologies for greater sophistication and diversity in construction projects are relevant. Also continuous implementations of prototype systems in actual construction projects to show the clear goals and concept. The implementation requires clear strategy promoted as a policy of construction industry, which aims to create new production systems associated with new business systems by introducing innovative material technologies and environmental preservation technologies.

2. TECHNOLOGY FUSION IN BUILDING CONSTRUCTION

Technology fusion is an emerging methodology proposed by Dr. Kodama. By fusing technologies, companies can create new products, markets, and industries, and remain ahead of their competitors. Technology fusion blends several previously separate fields of existing technology. Three fundamental principles can help companies implement a fusion strategy. First, let the market drive R&D, not the other way around, through a process called "demand articulation." Second, develop a strong intelligence gathering capability both as a defense mechanism against competitors and as a source of new ideas. Third, and most important, take part in cross-industry R&D projects [2].

Reviewing the past technology development process in Japanese construction industry, advanced technologies have been introduced to improve construction efficiency as a fusion of prefabrication, information, automation and construction technology. In the end of 1960’s, large construction companies started to develop super high-rise building systems and industrialized building systems reflecting economic boom and deregulation. Major technologies, which enabled super high-rise building systems, were high-stress steel, high-performance tower crane, and lightweight curtain -wall and computer-supported structural analysis developed by manufacturing companies. Those technologies were

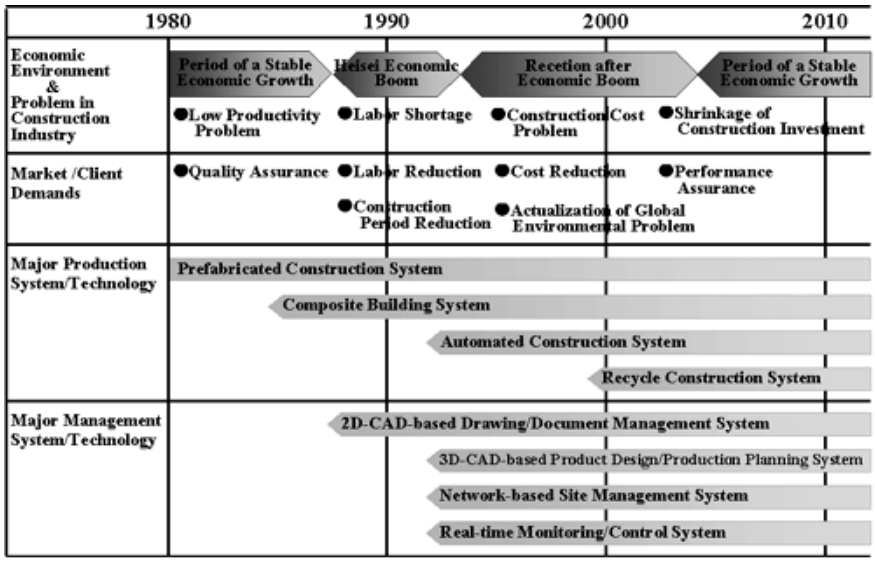

Figure 2. Process of Construction Technology Development in Japanese Construction Firms

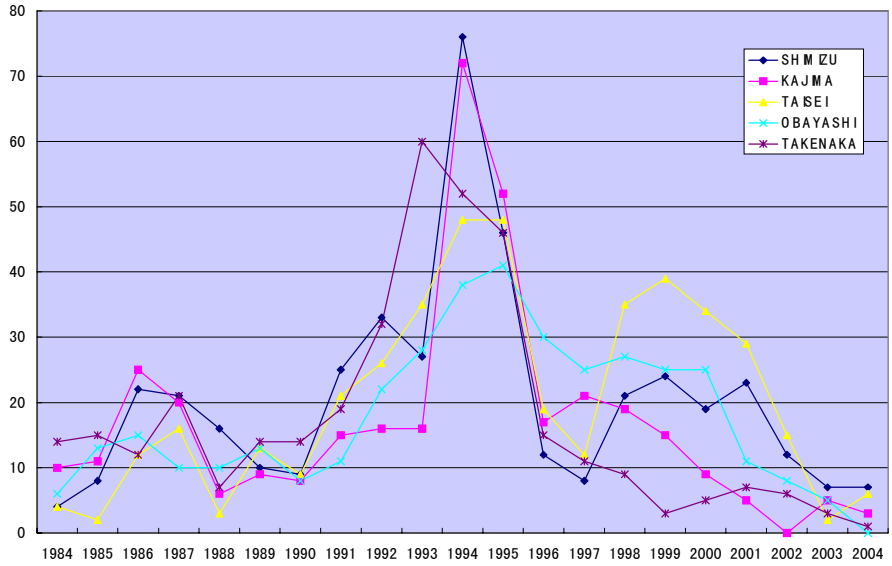

Figure.3 Changes in the Numbers of Patent Applications in the Field of Construction Automation by Top Five General Contractors in Japan

sophisticated and integrated with construction technologies, resulting in innovative building and construction systems. Also prefabrication technologies were introduced to develop industrialized building systems, which mainly applied to standardized condominiums. Not only construction companies promoted the developments but also manufacturing companies, electricity companies and chemical companies started the development to establish new business markets. The prefabrication technologies were also integrated with construction technologies, resulting in various types of standardized production systems with quality control techniques.

In the middle of 1980's, many large construction firms have started huge amount of investment to adapt innovative automation and information technologies to building construction based on increasing construction market. At first, many of the efforts were being carried forth in the context of the Computer Integrated Construction (CIC). To implement CIC, a systematic approach for applying computerization and automation to building construction by illustrating future vision of building construction was introduced.

The visions are represented as conceptual models to develop CIC by carefully investigating the functional distributions among design, engineering, planning, procurement, construction and required processes. For example, Shimizu's model was divided into four major functions: (1) Integrated design/construction planning system, (2) factory automation system, (3) site automation system, and (4) Multi-project management system with central project database. These conceptual models described strategies to exploit innovative technologies among improved functions.

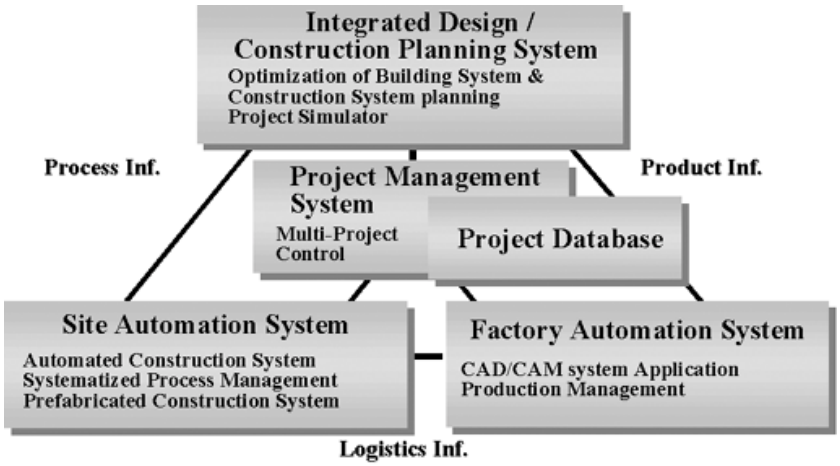

Figure 4. Conceptual View of Computer Integrated Construction

Applications of automation technology to building construction had been started as development of construction robots, which aimed to resolve some of the difficulties associated with construction activities. Since the robots were developed as single-task oriented robots, they could not remarkably improve efficiency of whole construction processes and activities, because they can only improve a part of construction processes and activities. To attain highly improved construction process, automated construction systems were researched and developed. The systems were illustrated as all weather automated construction systems that aimed to eliminate the bad image of construction industry, to create better working environment like factory and to improve quality of the products by utilizing automation and prefabrication technologies.

Shimizu's automated construction system is named SMART system, which automates a wide range of construction procedures, including: the erection and welding of steel frames; the placement of pre-cast concrete floor planks, exterior and interior wall panels; and installation of various units. The system utilizes prefabricated components extensively including columns, beams, floorings and walls, and the assembly of these components is simplified by the use of specially designed joints. In addition, this assembly process is orchestrated by real-time computer control, resulting in construction site operation in a highly automated way. The heart of the SMART system is composed of the lifting mechanisms and automatic conveying equipment installed on the operating platform, which is ultimately to be the top roof of the building. Steel-frame columns, beams, floorings and walls are automatically conveyed to designated locations, where they are effectively assembled and mounted with specially made joints. The steel-frame welding process is also automated with the invention of an automatic welding machine. When one of the floors of building is completed, the entire automated system is lifted vertically and the work for next floor commences immediately. Thus construction work proceeds systematically, floor by floor, until the whole building is completed. The SMART system also provides complete all-weather enclosure for site, accommodating satisfactory working conditions and safety, and leading to higher quality and durability for the product.

Reviewing labor productivity which is almost equal to efficiency of construction site work, labor productivity has been declined since 1990, however that of whole industry, especially labor productivity of manufacturing industry has been expanding, that means R&D investment has not effectively contributed to increase value of construction industry relatively compared with manufacturing industry.

Current challenging technology fusions are brought by comprehensive applications of IT systems. Since the middle of 1990's, Japanese construction industry has been involved in a severe recession. Construction companies had to improve their performance more and more by introducing information technology at whole business processes, functions and organizations due to the rapid changes in construction market. The technology fusions are well depend on 3D-CAD system, which is effectively applied to product design, production planning, real-time monitoring of construction process, control of transportation equipment in execution stage, and web-based communication system for site management. By utilizing those IT systems, a remarkable progress has been made in the field of integrated management of process, organization and product. Also the applications promoted knowledge fusions as well as technology fusions.

Recent needs for global environment preservation is making another technology fusion that is concrete recycle system. However prefabrication is useful to reduce construction waste, recycling of concrete waste produced by demolition is critical in present construction industry. To solve the problem, construction system associated with closed-loop concrete recycle system has been developed by introducing inverse manufacturing technology. Thus technology fusion is regarded as a key issue to innovate construction technologies.

3. KNOWLEDGE FUSION IN BUILDING CONSTRUCTION

In contrast with technology fusion, knowledge fusion has been introduced to construction industry as activities of organizational knowledge creation. In manufacturing industry, the series of researches with regard to organizational knowledge creation have been performed by Nonaka [4]. Our research started from the application of the framework presented by Nonaka to building construction. The integrated organizational knowledge creation model illustrated by Nonaka presents dynamic interactions as four types of activities: socialization, externalization, combination and internalization.

When the concept is applied to building construction, the transmission of expert skills and implicit knowledge through actual jobs from a skilled engineer to an unskilled engineer is socialization. Documentation and standardization of personal or group know-how is externalization. Systematization of documented knowledge in design, engineering, planning and management by computer programs is combination. Knowledge acquisition through development of new technology based on already possessed technologies is internalization.

Our focus here is on internalization and externalization, which are caused by interactions between implicit knowledge and explicit knowledge. Since the organizational knowledge creation does not limit to take one-way exploration starting from person level, a creative organization should have a system or a structure, which can explore linkages between four modes of knowledge creation.

In construction industry, researches on constructability presented similar results. The research pointed out the need for increasing understanding of the type of knowledge involved in experiences from engineering and construction projects. Constructability improvement is recognized as the evolution of four interaction modes of knowledge creation based on opportunities to better capture and transfer experiences and knowledge between design and construction. Since constructability researches took analytical and formulated approaches, the utilization of exogenous source of knowledge and combination of formalized knowledge are relevant.

Consequently, emphasis has been put on documentation and computer utilization to establish database and knowledge base with constructability. The activities are viewed as combination and externalization. Reflecting these researches, our focus is put on the dynamism of organizational knowledge creation, especially effective mechanisms to be adapted to project-based companies

Usually, the knowledge used in design and construction is divided into two types: (1) Implicit knowledge such as evaluation and application of building systems and construction systems, which are acquired through experience and are possessed by individual designer and planner; and (2) Explicit knowledge such as composition and functions of building systems and construction systems, which are shared as technical standards among groups, departments and organizations and are usually stored in the form of documents.

Reviewing successfully applied construction technologies, design, engineering, planning and management knowledge associated with the developed technologies are recognized as implicit knowledge at the beginning of development. According to the exploration of development, such knowledge is transformed into explicit knowledge such as technical standards of application procedures in the form of documents. The explicit knowledge is applied to actual building projects, and then the technologies require further improvement and sophistication to be more useful ones, such as hybrid building systems, automated construction systems and advanced computer applications. These developments need integrations and interactions among different types of knowledge in various disciplines.

Consequently, new implicit knowledge in design, engineering and construction is created through the integrated and interactive investigation by development organizations. Thus organizational

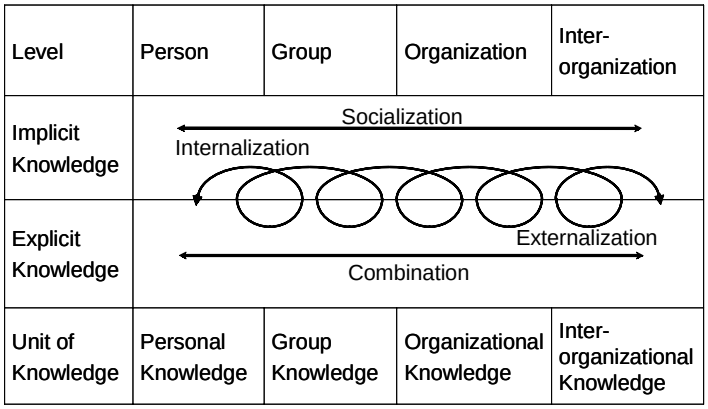

Figure 4. Evolution of Organizational Knowledge Creation

knowledge creation is performed as dynamic circulation and interaction among implicit knowledge and explicit knowledge through different levels of development stages. On the other hand, we see poor knowledge creation in many cases. Many technologies become out dated due to the lack of organizational knowledge creation.

One reason why the impact of the organizational knowledge creation approach on construction companies will be crucial is that it supports high level coordination between human and computer. The second strength of this approach is that it will provide the well-organized environment for transmission of information and knowledge, as the prerequisite for the use of an object-oriented approach in the integration of information and knowledge. This will remove current poorly coordinated transfers of information and knowledge between the various organizations. The environment will also provide more flexible decision making process among all critical design and planning functions. Thus organizational knowledge creation in building construction should be promoted to innovate construction industry.

4. CONSTRUCTION INNOVATION BY TECHNOLOGY AND KNOWLEDGE FUSION

To investigate the future strategy to innovate construction industry, it is important to introduce a structured way. Originally technology and knowledge fusions support a high level of coordination among process, organization and product. The systemic approach will provide a well-defined environment for the effective strategy for exploitation of the information technology to promote technology and knowledge fusions.

4.1 Management of technology by an integrated production system

Management of technology is defined as re-organization of potential construction technologies to efficiently resolve some of the difficulties associated with market demands for low cost and high standard and with increasing competition. Since construction technologies have been developed and stocked as individual or elemental technology to solve specific problems in general. However they are efficient as technology itself, inappropriate combinations of those technologies introduced by individual and insufficient investigations often cause contradictions and complexities in construction stages, resulting in losses of time and expense. Therefore organizationally integrated subsystems to simulate and define an optimal construction system as a best mixture of enable technologies are relevant.

In CIC concept, the construction system has been illustrated as a site automation system known as SMART system. The system is a portion of strategy for construction innovation that covers construction technologies for super high-rise buildings including automated transportation system of prefabricated components, jacking-up systems of operating platform and real-time monitoring of simultaneous production processes with various machines.

However higher sophistication of an automated construction system is implemented, economical changes in construction market forces the technology to be modified either to reduce automation level of the construction system or to seek an alternative construction system based on other concept. The former approach is to restrict applications of automation areas to adjustment of transportation machines that are difficult in manual control The later approach is to focus on material transportation system

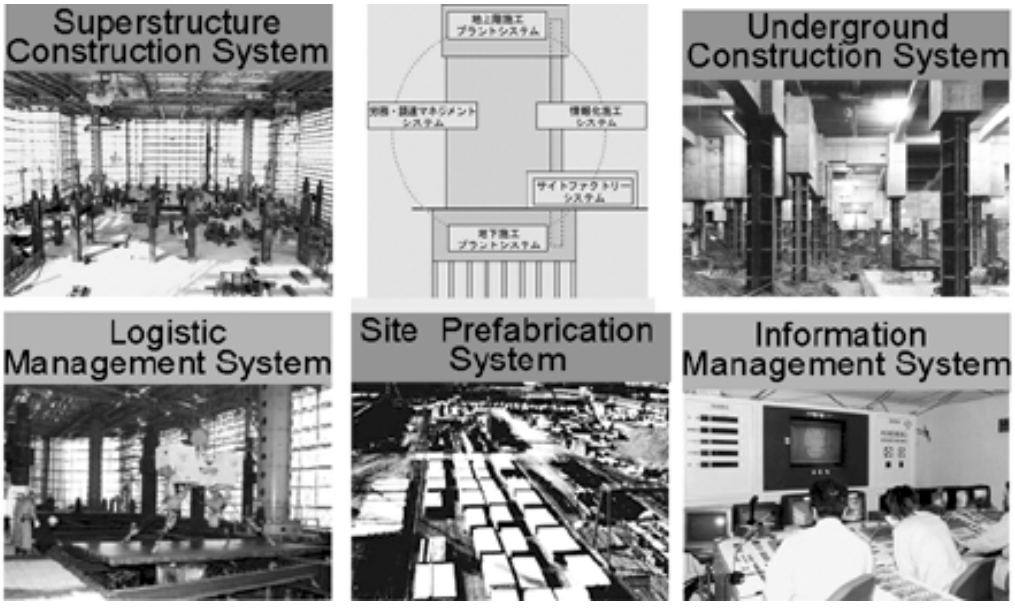

Figure 5. Conceptual Composition of An Integrated Production System

and its control system by intensive utilization of network, database, monitoring and control systems. A systemic strategy is currently undertaken to explore and to combine the both restructuring and alternative approaches to be a new paradigm of physical construction system from a viewpoint of technology management.

Integrating engineering hardware and management software composes the physical model of proposed construction system. The hardware system is consists of three physical engineering subsystems: (1) Construction plant system for superstructure to systematically incorporate transportation and assemly of prefabricated components and units with minimized temporal facilities and, (2) Construction plant system for substructure to widely introduce mechatoronics technology under simultenuos construction of superstructure and substructure, and (3) Site plant system to assemble components and to supply as units for construction plants.

The software system organizes two complemental management systems: (1) Logistic management system that covers package planning and procurment of materials and labors, and (2) Production information management system that incorporates the functions of analysis, simulation, monitoring and contorol with three plant systems.

Among those subsystems, production information management system is an integral part of the proposed construction system to adopt optimum information technology based on characteristics of construction plants to improve engineering efficiency as a total sysytem. Another function of production information management sysytem is to improve management efficiency by sharing production information with quality, cost, deivery, safety and environmental effects among participants of the project via project database and network systems. Thus strategy in management of technology is set up to integrate construction technology and information technology by subdivision and restructuring of physical construction systems from a viewpoint of production information management.

4.2 Management of product and process by concurrent and collaborative environment

The decision-making problems in a construction project often caused by precise subdivision of project processes and functions due to complexities and varieties in current construction projects. Consequently ineffective integrations of information, knowledge and technology are found especially in early project stages. The process-to-process and function-to-function information transmissions make decision-making processes more complicated, which are recognized not only in internal project processes but also in external project processes with participants of clients, design/engineering firms, constructors and suppliers.

In case of large-scale construction projects, a lot of time is spent to exchange information among project participants through value engineering, constructability investigation based on incomplete detail design, and coordination with design documents and construction drawings. Consequently early introductions of construction knowledge and information in a form of concurrent design and construction planning function is important

To realize the function, two types of process integration are required: (1) Horizontal integration in a project organization as a collaborative work environment among designers, engineers and managers through optimal combinations of enable construction technology and information technology, and (2) Vertical integration in project processes as a

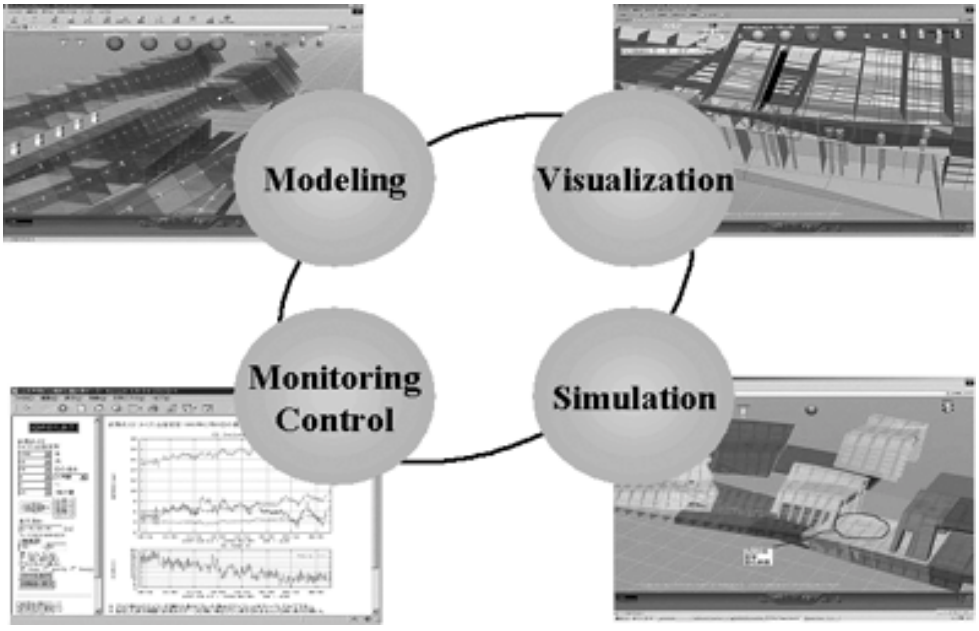

Figure 6. Functional View of 3D-CAD Based Production Information Management

concurrent work system among designers, engineers, constructors, fabricators and suppliers. The collaborative work environment in practice should be established as product design system by integrated design and construction drawing using CAD and EDI technologies.

The concurrent engineering environment for construction simulation should be established under production planning system using 3D-CAD systems with formalized building/construction information models by which various simulation systems are interactively utilized. The 3D-CAD applications should also be carefully investigated by considering efforts in data input and benefits by repetitive use of data. Currently product design and production planning are key issues towards total product and process innovation, and most of efforts should be undertaken in this direction with standardization of product and process models.

4.3 Management of organization by IT-based knowledge management system

Recent innovation in business process reengineering has provided an effective methodology to organizationally acquire, utilize and create useful knowledge associated with design, planning and management of construction projects. Originally IT applications to different levels of organization contain standardization of work flows and externalization of implicit knowledge to be utilized as well-organized processes and explicit knowledge to improve total efficiency of the project processes

Current IT-based applications to share information and knowledge among individuals, groups and organizations in construction projects are divided into four major functions: (1) Internet-based real-time monitoring systems to share measured data with structual performance, and transportation information of building materials among site engineers and supporting engineers in headquarters, branch office and institute of technology; (2) Web-based information management system to share information with construction progress, pending issues, and visual information of construction site, among clients, designers, engineers, constructors, fabricators and suppliers; (3) Total project management system among different project blocks at site, and (4) Knowledge management system among same type of building projects such as high-rise condominium, hospitals and semiconductor factories that require specific engineering knowledge and technical information.

Since management of organization aims to integrate project functions to realize the customer satisfaction with a construction project including quality assuranc e and performance assurance under requirements and constraints, optimal combination of design, engineeri ng, procurement, construction and maintenance syste ms by organizational knowledge management are nec essary. Therefore, lifecycle management of informati on throughout feasibility study to maintenance and re novation should also be highlighted.

4.4 Management of Building Resiurces by Reuse amd recycle Systems

Companies of in various fields have been raising emphasis on environmental programs. In the construction industry as well, companies are taking steps to reduce their impact on the environment. In Japan, new scheme has been created by the amendment of the low for production to effectively utilize recyclable resources. The promotion in construction industry is performed as 3R (reduce, reuse, and recycle) activity. Two types of approaches have been undertaken to pursuit zero emission from a viewpoint of technology. One is an improved approach to pursuit for zero emission thorough development and applications of efficient construction technologies to realize the 4R(refuse, reduce, reuse, and recycle) program at project level. Another is an innovative and challenging approach thorough development of relevant material recycle systems at company level, by introducing innovative technologies such as biotechnology. We believe both approaches are necessary to relentlessly pursuit for zero emission in construction, by promoting the 4R program at project level.

On the other hand, major innovative approach is posed on recycling of construction by-product. The major resource to be recycled in construction industry is concrete, which occupy about 40% of total materials used in whole Japanese industry. Amount of concrete waste estimated will exceed the demand capacity of road sub-base in near future, and capacity of disposal facility will not be able to accept concrete waste.

To solve the problem, closed-loop concrete recycle system has been developed by introducing manufacturing technology. A heating and rubbing plant is settled to a construction site to reduce transportation of concrete waste caused by demolition of existing building. Using the plant, huge amount of decomposed concrete is divided to coarse aggregates, fine aggregates and pulverized materials that are recycled as recycled concrete and soil improved materials for the construction project.The other innovative approach is illustrated as development and application of innovative structural materials. Innovative structural materials include super high-strength concrete, super high-tension steel, ultra fine-grained steel so called ultra steel, and innovative composite materials represented by carbon fiber reinforced plastics. These innovative structural materials have feature of not only high-strength as twice as ordinal concrete and steel, but high durability as twice as ordinal concrete and steel, high rigidity and high corrosion resistance. Thus innovative structures using innovative structural

materials make their lifetime longer and reduce amount of materials by developing non-welding joint between building components which allow them to be reused. The buildings designed by innovative structural systems can be viewed as sustainable buildings. Our target is to develop innovative structural system using innovative structural materials and also to develop structural health monitoring and self-repairing technologies which are to be required in realizing sustainable buildings.

In early 1980's, Shimizu had started a technology development project to seek new structural materials toward 21st century which substitute steel products and rebar. As a result, over 200 new ideas with new materials were identified including super high-strength concrete, fiber reinforced plastics and carbon fiber reinforced plastics. Also several types of innovative structural syatems and buildings were researched to adopt such new materials.

Among such structural syatems, space truss structure system was at first focused, because it has a simple structural system which can also make use of the feature of light-weight easily. The structure divides an external force into only axial forces of members. Secondary a mixed application of super high-strength concrete and ultra steel is set up for a triple skeleton structure system.Triple skeleton structure system consists of three levels of skeletons according to renewal cycle time. The first skeleton is composed of seismic isolation system and high rigged core to be used for 100 to 200 years. The second skeleton is built by ordinal steel structure system with recycle-oriented connecting mechanism such as ring-panel non-welding method to be reused every 50 years. The third skeleton is the most flexible skeleton by light steel structure system to be reused every 25 years. Thus the triple skeleton structure system is regarded as a sustainable building system with innovative materials.

With the development of such innovative structure systems, mechanisms to secure structural health are also to be developed. Actually the needs for a structural health monitoring system for civil and building structures are emerging recently. This figure illustrates an image of structural health monitoring system.

The system intensively utilize sensors which are installed in civil and building structures. When earthquake or typhoon make stresses in building, sensor system installed in a building detects failures, defects and cracks and reports information to a data center. The information is also transferred to designer, constructor and owner of the building to acknowledge damages without manual inspections.

A structural health monitoring system using FBG-based optical sensors is installed in a 12-story steel building. The building is equipped with several panel dampers made of low-yielding steel panels. The panel dampers work as energy sinks to reduce the vibration response of the building when subject to a larger earthquake. The structural health monitoring system is hence installed to ensure the structural integrity by monitoring the response of the building. FBG-based optical sensors employed for the system were newly developed to measure strain, displacement and temperature. The installed system was verified to function properly when careful tuning of the system was made.

In Japan, nanotechnology and material research-and-development project team was installed in the bottom of the Council for Science and Technology, and the Ministry of Public Management, Home Affairs, Posts and Telecommunications, the Ministry of Economy, Trade and Industry, the Ministry of Education, Culture, Sports, Science and Technology, and the Ministry of Land, Infrastructure and Transport are

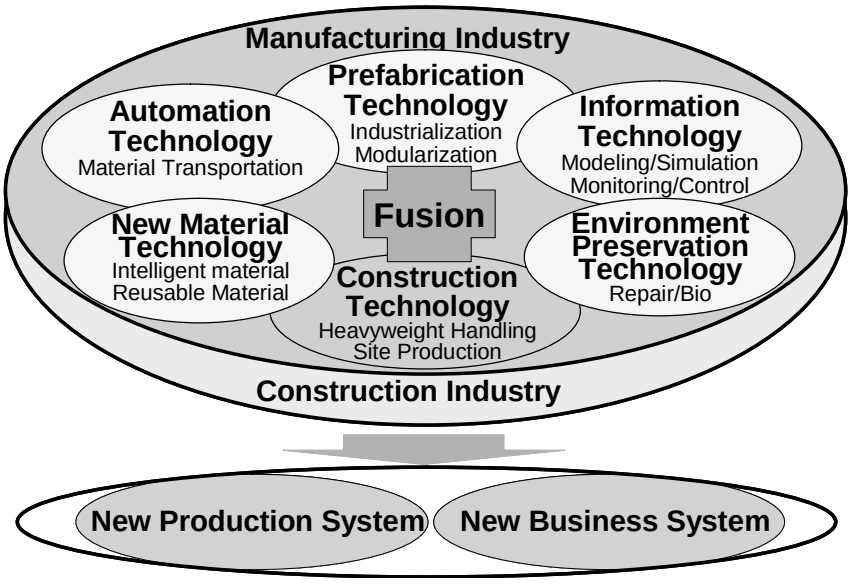

Figure 7. Future Directions of Construction Technologies

cooperating and promoting under initiative of Cabinet Office. Innovative structure material was taken up as one of the cooperation project, in which not only research and development are promoted through coalition among offices and ministries, but environmental consideration of demonstration in model projects, standardization as JIS, and collaborative support for commercialization and industrialization of innovative structural materials are to be undertaken.

The project schedule is settled for 5 to 7 years, including Research and development of a material utilizable over a short period of time, research and development of a new connection part, research and development of material, connection, design and construction method, research and development of a material utilizable over a long period of time, and structural health check and monitoring. Also the experiment in an actual proof models are planned for buildings and bridges. Innovative materials and methods will reduce the time and cost of construction and greatly extend facility performance, functionality, aesthetics, affordability, sustainability, and responsiveness to changing business demands.

Reviewing past development of innovative technologies, new building systems and structural systems have been realized by development and utilization of innovative structural materials such as high strength steel, high-strength concrete and carbon fiber reinforced plastics. Furure automation technologies and inforamtion technologies will also well depend on the development of new structural sysytems by innovative materials.

5. CONCLUSION

For future construction industry, technology and knowledge fusions are key methodologies. To promote technology and knowledge fusions, information technology should be viewed as key technology for project-based construction firms. Introduction of advanced IT systems are well depend on the levels of fusions among information technology and construction technology. Also efficiency of IT systems depends on the clear definition of engineering and management functions of the project. Among such applications, communication systems based on Intranet using web-groupware for project management are widely utilized to share information and knowledge that imply future directions of IT-based knowledge management methodology.

To introduce effective IT systems to project level innovations, IT strategy should be carefully investigated from systemic viewpoint to utilize concurrent and collaborative environment for product and process management, an integrated production system for production technology management and organizational knowledge management system for organization management.

Also technology and knowledge fusions require implementation of prototype systems continuously to be adapted advanced technologies to actual construction projects such as development of SMART system, maintenance of clear strategy promoted by top management such as computer integrated construction, and fusions of new production systems and new business systems toward a industry fusion.

National development program of innovative technologies with a dream needs to be created for economic revitalization. Technology innovation and economic revitalization through active promotion of cooperation among industry, academia, and government. Construction industry contributes to the improvement of global environment of the future generation in cooperation with other industries, academia and government.

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EVENT-BASED DISTRIBUTED PLANNING & CONTROL SYSTEMS FOR PROJECT DELIVERY

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Abstract: As modern projects become increasingly complex, dynamic, and pressed for time, delivering them on time and on budget using traditional means is becoming more and more challenging. Strategic Project Solutions, Inc. (SPS) has successfully extended Lean Manufacturing techniques to complex production-based project environments, namely large construction and industrial projects.

To support large and complex project-based production systems, such as construction, SPS has developed a web-based real-time distributed project management tool. It provides distributed cross-functional teams a means to better control workflow at the production (design, fabrication, assembly, etc.) level. This system, with named SPS Project Suite, has been implemented on several large construction projects, including London Heathrow Airport Terminal 5 Expansion (T5) and Channel Tunnel Rail Link (CTRL) Contract 105.

SPS Project Suite combines the principles of Last Planner, Lean Manufacturing, and Project Management with web technology to enable project team members to better coordinate interfaces, manage shared resources, and identify where performance improvement efforts must be invested. The use of web technology enables cross-functional teams to work remotely. SPS Project Suite's single database contains all production-level workflow information related to a project. The single database enables resource optimization at the highest level through a real-time overview of the project's production status at any point in time.

This paper describes how SPS's web-based real-time distributed production control tool benefits projects that are large, complex and dynamic.

Keywords: Production Control, Project Management, Distributed Planning and Control, Remote and Real-Time Collaboration

1 INTRODUCTION

Increasing globalization and the competitive nature of free markets have combined to require organizations to continuously develop and effectively deliver new offerings to their customers. Not doing so in most industries is the kiss of death; doing so consistently enables enterprises to gain and maintain competitive advantage.

In order to develop and deliver new offerings that meet customer needs, organizations undertake projects, which require the definition, design, implementation, operation and decommissioning of temporary processes, systems and structures. . There are numerous examples of organizations that have successfully developed robust project management capabilities and realized ongoing competitive advantage, such as Toyota and its revolutionary approach to product development.

As projects have become an increasingly critical element of organizational success, academics and industry practitioners have been searching for, developing and applying alternative theories, principals, methodologies and tools designed to significantly improve project outcomes. One noteworthy development is the introduction of distributed planning and control to the project delivery process.

2 SPS PROJECT SUITE

Strategic Project Solutions' (SPS) production-based project management suite (SPS Project Suite) enables stakeholders involved in project-based endeavors to successfully apply distributed planning and control by effectively embedding modern management principles, including the Last Planner methodology [1,2], Lean Manufacturing techniques [4,5], and Project Management practices [3]. The SPS Project Suite, which is web-based, effectively combines real-time transparency, process improvement, and effective resource utilization. It also allows project-level integration by enabling better coordination of interfaces, improved management of shared resources, and clear identification of where performance improvement efforts should be invested. The SPS Project Suite contains all of a project's control level workflow

information in a single database and provides a real-time status of a project's production system, thus enabling resource optimization at the highest level. Finally, the SPS Project Suite reinforces and leverages the use of cross-functional teams by forcing the changes in underlying behavior required by modern management principals.

The SPS Project Suite enables users to systematically plan and control production-level workflow and supporting material deliveries, while simultaneously facilitating learning and measuring throughout the project delivery process. In the construction industry, this translates into immediate benefits for design, engineering, fabrication, and both pre- and final-assembly phases of projects. In software development, immediate benefits are realized in the process design, architecture design, programming, testing, and rollout phases of a project.

2.1 Last Planner Methodology

Ballard and Howell point out that, in the traditional construction management approach, tasks to be carried out are defined prior to the start of construction and it is assumed that resources will be available when needed [2]. It is then up to production crews to gather what resources they have and to follow the schedule as best they can. This often results in a situation where the tasks cannot be performed as scheduled because actual resource availability does not match the assumed resource availability.

To alleviate this situation, Ballard and Howell proposed the Last Planner Methodology (Figure 1), which focuses on injecting reliability in planning by stabilizing workflow at the production level [2]. The main purpose of the Last Planner is to shield workers from the uncertainties they do not control through active identification of constraints (constraint analysis).

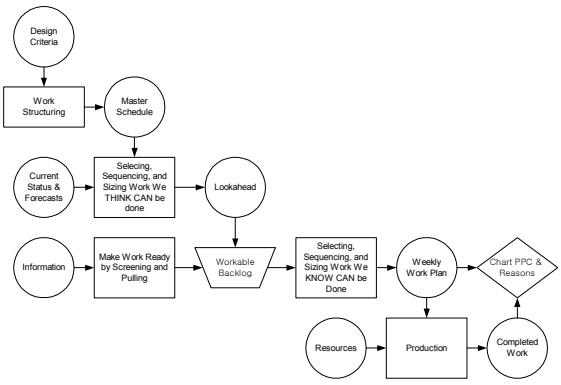

Figure 1. Last Planner Methodology

The SPS Project Suite extends Last Planner Methodology by incorporating constraint analysis into a distributed planning and control system where all project participants are responsible for performing constraint analysis. This assists project participants in identifying interfaces and predecessor/successor relationship between tasks, while achieving higher reliability due to making work ready to be performed. SPS Project Suite allows users to use different planning horizons based on type of work carried out by the production teams (e.g., daily production plans for construction teams, weekly production plans for design teams, etc).

2.2 Lean Manufacturing Techniques

The SPS Project Suite embodies specific Lean Manufacturing techniques [4] to align progress of production work with the supply of material, equipment, labor, and information. One of these techniques is "stopping the assembly line to immediately repair quality defects". The SPS Project Suite adopts the technique above in that it helps identify defective tasks ("constrained") early on, before resource is allocated to perform them. It also prevents defective tasks from being passed down the line (which corresponds to "stopping the assembly line"). Additionally, the project suite supports "pulling materials through the production system to meet specific customer demands." It allows the pull of required resources by streamlining the communication and coordination process for material supply and pulling material based on the status of the project's production system. It also supports "clearly documenting, updating, and constantly reporting the status of all process flows to all stakeholders involved" in that it captures tasks that are being done and not done on a real-time basis.

2.3 Project Management Practices

The SPS Project Suite incorporates Project Management Practices such as Work Breakdown Structure (WBS) management, scheduling, forecasting, and document control with production control.

The WBS management capability within the SPS Project Suite allows production teams to structure the work from a production perspective while maintaining alignment with the WBS hierarchy specified by the project controls (Figure 2). Thus, progress and statistics collected at the production level can be aggregated and assigned to the appropriate level within the WBS.

The SPS Project Suite also allows all project participants to view near real-time transparent project status in Gantt chart format (Figure 3). It can be configured to display the target, actual, and forecast information. The SPS Project Suite also supports document management capability by linking documents to their associated production activities.

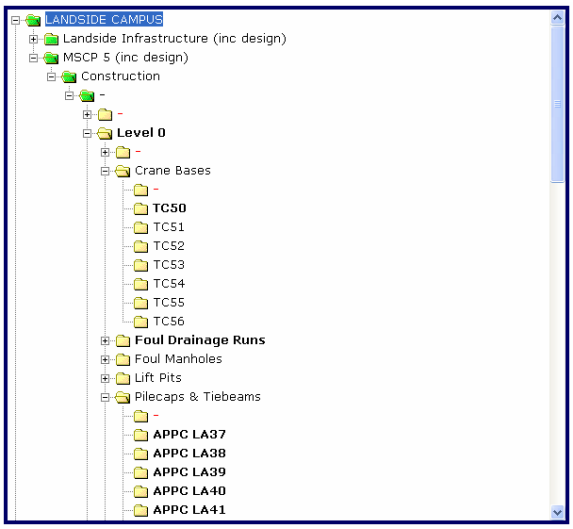

Figure 2. Work Breakdown Structure Management in SPS Project Suite

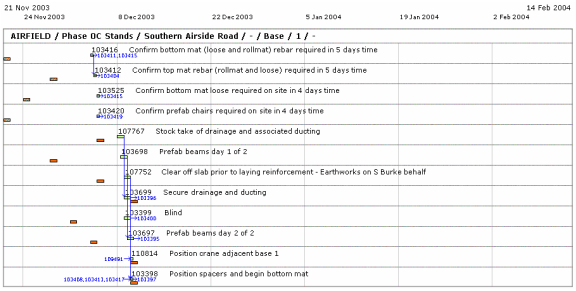

Figure 3. Gantt Chart Report from SPS Project Suite

2.4 Functionalities

The SPS Project Suite facilitates the co-creation of detailed weekly/daily production plans that are linked to project milestones. When tasks are not completed as planned, the SPS Project Suite mandates the entering of reasons for non-completion, which enables learning and continuous improvement that leads to improved planning reliability and project performance (Figure 4).

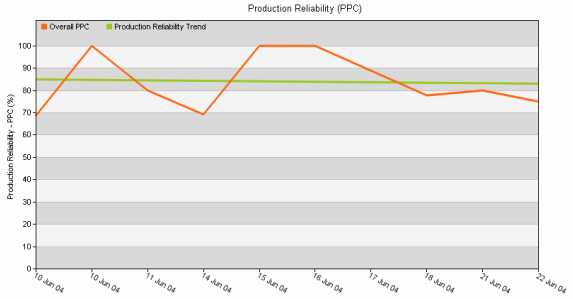

Figure 4. Production Reliability in SPS Project Suite

The SPS Project Suite also allows project related data to be attached to either a single task or a set of tasks. A common example of this functionality in construction is attaching 3D/4D product models to either a task or set of tasks. The simultaneous visualization of product and process facilitates a concurrent engineering approach, which significantly improves the efficiency and effectiveness of the project delivery process. It also allows all users to have complete transparency of whether the project and project teams are on schedule by measuring the progress against their own schedule rather than one created by a central planner, and identifies schedule variation of the production-level, which is where it can and should initially be detected and addressed.

3 APPLICATION

The latest production version of this system has been implemented on several large construction projects under several names (e.g., ProjectFlow, ToolFlow, SPSFlow). Some on-going projects include London's Heathrow Airport Terminal 5 Expansion (T5) [http://www.baa.com/main/airports/heathrow/terminal_5_frame.html] and the Channel Tunnel Rail Link (CTRL) Contract 105, [http://www.ctrl.co.uk/] where it is helping the production teams achieve outstanding results.

T5, like many large, complex and dynamic projects, faces serious logistics challenges. Although there are large number of simultaneous construction activities (more than 100 trucks/hour will be entering and leaving the site through a single gate, and more than 500 construction crews will be working simultaneously on over 80 subprojects), the lay-down and staging area on-site and off-site can only accommodate approximately one day's worth of material. This problem is exacerbated by the single point of access to site, local policies on delivery times, as well as congestion around the airport.

To minimize the effect of such constraints, the SPS Project Suite is currently being used at T5 to pull material to the workface from the suppliers on a daily basis according to daily production plans, which reflect in real-time the status of the project's production system. Transparency of the site daily progress allows suppliers to monitor usage of their material on site and release deliveries accordingly. Likewise, transparency of the supplier's progress allows site to track expected material delivery time and plan accordingly.

SPS has also been working with site teams on all involved projects to increase planning reliability so that the information given to suppliers is accurate and less likely to change on a daily basis. At the same time, SPS is involved with suppliers in an effort to reduce their lead time and increase supply reliability.

4 CONCLUSION

A web-based real-time project management tool that enables distributed planning and control (the SPS Project Suite) encapsulates a new way to manage projects has been developed and successfully

implemented on several complex and dynamic projects. It integrates project and production management, guiding the production teams to execute work that progresses the project based on the right sequence and timing. The collected reasons for plan failure also allow teams to continuously improve by working on the root cause of the failures.

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Evaluation of Physical Modeling and 3-D Simulation for Planning Accropode Placement

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Abstract: Accropodes are non- reinforced artificial concrete blocks used for the protection of the breakwaters and other coastal structures. There are numerous conditions that should be satisfied for the successful placement of the Accropode. In the study done two tools are developed for the understanding of the various placement conditions of Accropode. Experiments are done to compare the two tools and conventional method using text and sketches. A benefit cost analysis of the different tools is done. Results of experiments are analysed and reported. Conclusion has been drawn out of the study.

Keywords: 3D Simulation, Construction Planning, Breakwater Construction

1. INTRODUCTION

Accropodes are non- reinforced artificial concrete blocks utilized as protecting armour on breakwaters and costal structures. The shape of this block is complex and optimized for wave energy dissipation. However in-order to provide effective protection, the pattern of placement of these blocks have to satisfy numerous conditions. These conditions are primarily based on the spatial orientation of each block with respect to the neighboring blocks.

The blocks can weigh between 2 - 67 T [1] and are slung with a single rope and placed with a crane. The orientation of placement is governed by slinging direction. As the productivity of placement of these blocks contribute significantly to the completion of the project, it is critical that the block placement is planned meticulously and executed without any errors. If any error is found at a later stage, it requires the removal of the entire row of block to correct the error – the multiple handling of the blocks can cause damage and lead to delays.

On a large harbour breakwater project it was observed that planners found it complex to understand the placement conditions initially. Further, the engineers executing the plans on site
also did not clearly interpret and understand the conditions of placement. As a result there were numerous delays and rework. The objectives of this work are to (i) investigate if the planning and placement process can be made accurate and error free from the initial stages through the use of Physical models and 3-D simulation (ii) analyse the cost-benefit of these techniques.

The experiment involved 3 groups of novice planners. The first group was allowed to learn the placement conditions using written text and sketches – the conventional method. The second group was allowed to learn the placement conditions using scaled physical models of the Accropodes and cranes. The third group was allowed to learn the placement conditions using 3D interactive graphical simulations. The understanding of each group was tested through questions on identifying errors in given placement as well as developing a placement design. A cost-benefit analysis of each option was then carried out.

The paper initially discusses details on Accropodes and its placement conditions, problems faced in planning and execution. Next, the details of the experiments conducted, development of the 3-D simulation model, the results of the experiments and a comparison of the techniques are presented and discussed.

2. ACCROPODE – DESCRIPTION

The Accropode is a non-reinforced concrete block specially designed for the protection of riverbanks and coastal structures. Figure 1 shows the components of a typical Accropode which is designed by Sogreah Ingenierie The Accropode is stated to provide robustness and stability in a single layer to give reliable protection while being easy to fabricate, store and transport. [2]

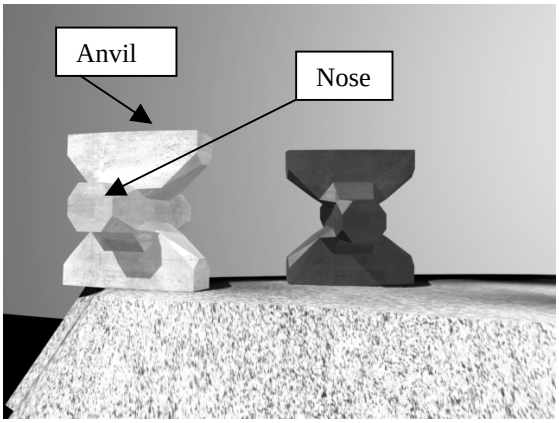

Fig. 1 Typical accropode with its components

Accropodes vary in sizes according to the level of protection required for breakwaters. Size of accropode may vary from $0.8m^3$ (2 T) to $28m^3$ (67 T) [1]

2.1 Accropode- Design & Placement

In designing an Accropode layer, three factors – the size, distance and orientation have to be specified. The size of the Accropode is based on the level of protection required at a section which in-turn is governed by the coastal parameters and the breakwater layout. The distance between accropodes is fixed on the basis of their size and given by an empirical formula [1]

For a specific section, this distance remains constant along the row and column. The orientation of the Accropode is critical for the proper functioning of the structure. There are set of rules specified by Sogreah Ingenierie to determine the orientation pattern in a section [1]. These rules are:

1. Blocks are placed in a single layer.
2. Interval between the centers of gravity of two blocks in the same row and column are equal.
3. Slinging attitudes must be varied and inclination of the blocks preferred.
4. Blocks shall be placed in deliberately varied attitudes, with neighbouring blocks having different attitudes.
5. No two blocks in the same horizontal row should be in contact.
6. Each block must be in contact with the underlayer.
7. Each block must key in between two blocks on the row below.
8. Less than one third of the blocks shall have the anvil parallel to the slope. Blocks in this attitude must be distributed throughout the facing and shall not be found in groups.
9. No two adjacent blocks shall have their anvils touching.
10. Placing density shall be fixed as per drawings.

2.2 Placement Method

Placing the Accropodes to meet design specification is critical to the functioning of the protective layer of the breakwater. During the placement if any block is found to be placed incorrectly, rework is required to make corrections. If an error is found in a section after it is complete, it can involve the removal of many interlocking neighbouring blocks to correct the error. This will certainly affect the productivity of placement.

In the current method of placement, the breakwater is divided into number of small sections. Each of these sections is then divided into numbered grid cells. Each cell is given a number and the accropodes, which are to be placed in a particular cell, is given the corresponding numbers (say 1, 2, 3 etc.).

The section of breakwater with accropodes and corresponding grids are drawn in AutoCAD. Coordinates for each accropodes are calculated and reduced to northing and easting, which are calculated with reference to a fixed base station. These coordinates are fed into a software, which guides the placement of accropode using GPS.

The use of GPS is enabled through a GPS guided crane. In this crane, the GPS antenna mounted over the tip of its jib and the signal is sent continuously to a computer installed in crane operator's cabin. On the computer, the section grid and the position of the boom tip in relation to the grid are displayed.

When placing an Accropode, the grid number unique to the Accropode is entered into the computer. Next, the software will show the target position and the current boom-tip position. As the Accropode is slung directly below the boom-tip, the 2D position of the boom-tip corresponds with the current Accropode position. As the boom swings/luffs, the position of the Accropode shown on the screen will dynamically change according to its actual position.
The crane operator has to ensure that the current position of the Accropode is over the specified target grid before lowering it and finally releasing it.

2.3 Rework

The GPS enabled crane facilitates the accurate placement of an accropode in its final position. However, the orientation of the Accropode is also a critical design requirement. There are no tools to assist the operators to ensure that the orientation of placement is accurate. This is done by the human expertise of the operators and then checked by expert consultants after placement.

After the completion of the placement in one section a check of the correctness of the accropode is carried out on the basis of ten conditions. During these checks wrongly placed accropodes are identified and marked. In order to correct the section the rework can be simple -involving one or two blocks, or very complex and involve lifting and replacing a number of blocks.

As discussed in the last section the accropodes are placed based on design specifications that ensure proper interlocking of blocks. Fig. 2 shows a typical Accropode face of a breakwater. As the blocks are interlocked, correction of a single block orientation can require the removal and replacement of an entire row. It can be seen from Fig 2 that rework can be a very complex operation, in-fact more complex than fresh placement. Further, during rework blocks can get damaged and might need total replacement.

During site visits to a breakwater construction project, it was observed that productivity of accropode placement was low as there was lot of rework in this activity. This affected the entire project productivity and exposed the contractor to high liquidated damages.

On further study and analysis it was found that the primary reason for the rework was that the placement requirements of Accropodes were not properly understood at the execution level. There is a learning curve for understanding the placement of the accropodes, as person gets more and more experience there is less chance of making error.

Fig. 2 Accropodes at a breakwater site

On the site visited the operators were learning on the project. This is not advisable as it takes about 2-3 months for them to learn the requirements properly. Further, as the requirements needs very good visualization and spatial capabilities, it is not easy to impart without appropriate tools.

The study done in this paper tries to flatten the learning curve by using different training tools. This study mainly deals with determining the capabilities of different training tools, to aid in improving the understanding of accropode placement design. Once placement design is understood it will reduce rework hence increase the productivity. The two tools used for this work are physical model based simulation and computer based 3D simulation. The results from these two tools are compared with the conventional method of instruction using the Text and sketches.

The following sections of this paper describe the tools, the experiments conducted, results obtained and conclusions made.

3. PHYSICAL MODEL BASED SIMULATION

Model trains, cars, boats, airplanes, helicopters and rockets give an opportunity to learn various phenomena which otherwise is very difficult to comprehend. Models of buildings, events, machines etc. helps deepen our understanding by providing concrete representations that engage our senses.

Model building is one way of coming to grips (sometimes literally) with aspects of our world that would otherwise be beyond our grasp. One of the tools used for the study, is physical model based simulation. In this tool, models of cranes and accropodes are used to simulate and hence aid understanding of accropode placement.

A tabletop crane model was used to imitate the movements of actual crane. The model can perform operations like swing, luff and hoist. Accropode models can be slung, lifted and placed with the help of the model crane.

Fig. 3 Placing Accropodes With Physical Model

This helped in simulating the placement process.
Scaled models of Accropodes were cast in using a custom made steel dye and high impact plastic with the help of an intrusion machine

4. COMPUTER BASED 3D SIMULATION

A 3D computer based simulation of Accropode was developed showing a set of eleven accropodes placed on breakwater. Accropode geometry is modeled in software called Maya.

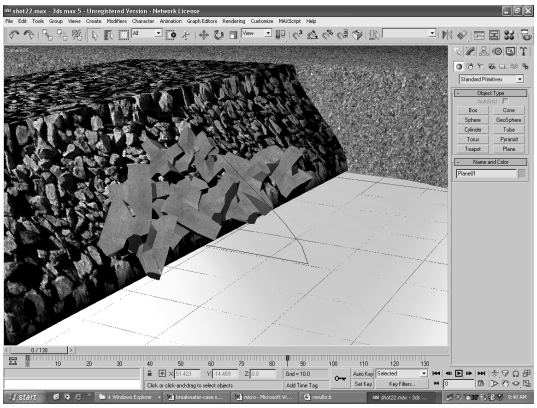

Fig. 4 Accropode Animation in 3D Studio Max

The simulation for accropode placement is modeled in 3D Studio Max [3] as shown in Fig. 6a and 6b. The advantage of such modeling is that the viewer can view the placement details as many times as required with a click of button. Further, the Accropode placement can also be viewed from different angles, to enhance the understanding on the placement orientations and slinging requirements.

5 EXPERIMENTAL METHODOLOGY

Purpose of the experiments was to compare the ease with which people understood placement requirements through the use of these tools.

The people who were chosen for the experiment were from mixed background. They were people with work experience from 2 to 7 years in construction industry. They had experience in supervising projects like building construction, heavy industrial and road projects.

The participants were divided into three groups. Each group was exposed to the placement requirement using:

1. Text and sketch (conventional method)
2. Physical models of Accropode and a crane model.
3. A totally computer based simulation of accropode placement.

Along with each of the above materials standard basic principles of placement of accropode were given to each participant. A single page write-up and few figures were also given to the participants of the experiment. A write up was given to provide basic information about breakwater and Accropodes.

A physical test-bed was set-up to test the understanding of the participants after they had learned the placement requirements using the respective tools. This test-bed consisted of a model breakwater slope and scaled models of Accropodes to be placed on the slope. The ability of tool to assist understanding the placement requirements was evaluated based on the accuracy with which a participant trained using a particular tool constructed the model on the test-bed.

Fig. 5 Placing Accropode Model on the Test Bed

The list of the parameters for which accropode placement accuracy was checked is as follows:

1. Placement on anvil or nose
2. Number of accropodes placed on anvil
3. Attitude of the surrounding Accropodes
4. Slope
5. Contact with under layer
6. Interlocking
7. Contact with surrounding Accropodes

To conduct the experiment 15 participants were selected based on their experience and background. Each participant was given about an hour to familiarize with the assigned tools and then tested individually. After the study period, participants were asked to construct the model on the test-bed. The accropodes placed were then checked for the accuracy.

After completing the experiment with one tool participants were exposed to other two tools and asked to compare the merit of all the three tools in their view. After exposing participants to all three tools six questions were asked to find out the merit

Fig 6a Computer Animation of Accropode Placement -Lifting

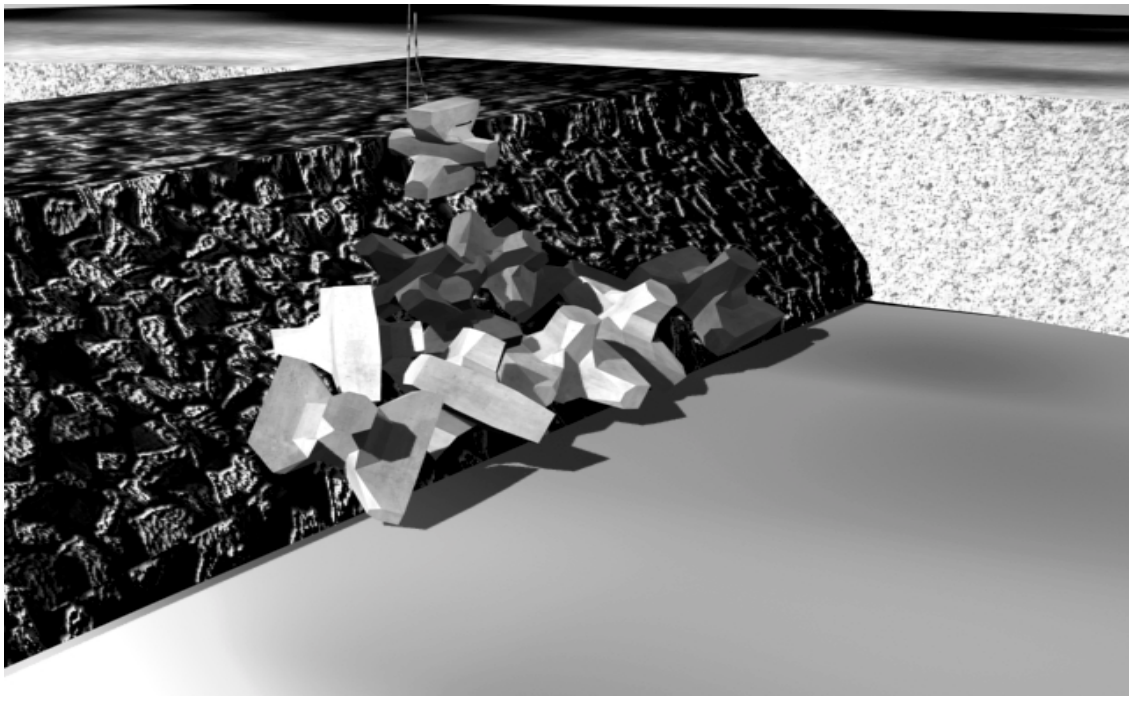

Fig 6b Computer Animation of Accropode Placement -Placing

of each tool. The questions, which were asked to participants, are listed below.

Q1. Which tool among the three was easy to understand?

Q2. Which tool gave you better understanding of the slinging positions?

Q3. Which tool helped you in visualising the total placement?

Q4. Which tool gave you better understanding of the interlocking?

Q5. Which tool gave you better understanding of the attitudes of the Accropodes?

Q6. Which tool would you recommend for explaining the Accropode placement technique?

6. ANALYSIS AND RESULTS

Out of fifteen participants, five were given Text and sketches, five were given physical model, and five were given computer based 3-D simulation. None of the five given the written material were able to place accropodes in correct position. Out of five who were given physical model of crane and accropode, three were able to place the accropodes in perfect manner satisfying all the conditions. Out of the five who were given computer based 3D simulation of accropode placement, four were able to place it in perfect manner satisfying all the conditions.

Thus a preliminary conclusion is that computer based 3D simulation and Physical modeling are effective in communicating the accropode placement technique, while a pure paper based approach has limitations.

The results from the questions asked to the participants were also in favor of 3D simulation model. But for understanding the slinging position of the accropode, physical model based simulation was found most appropriate.

6.1 Comparison of Tools

In comparing the cost to develop the computer model and physical model it was found that the costs of out-sourcing both to specialists were nearly the same. The charges for hardware/software usage and developers are major components of utilizing the computer model. The charges for mold and model development are the major components of the physical model. If in-house capabilities are to be developed for both it is likely that computer modeling will be cheaper as it can be shared with other requirements.

As the physical model gives the natural feeling of the placement scheme and method. It helps in understanding the various slinging procedure for accropodes. Further it shows the behavior of accropodes while they are slung and lifted. This might be valuable training for site conditions. Further, no special training or instructions is needed to train site personnel on physical modeling – they learn it naturally.

While computer modeling does not give a natural feeling of placement scheme, it is very effective in assisting the visualization of the process. The ability to display various angles simultaneously and design instructions based on common problems gives it a distinct advantage. Further, a computer animation can be stored and transferred to remote locations easily thus in terms of mobility and distributed usage also it has an advantage. However, people don't take up computer mode as naturally as they do the physical mode and there is some training required to enable them to use it effectively.

7. CONCLUSIONS

The placement of accropode on a breakwater face is critical activity. The orientation of the Accropode is critical for the effective functioning of the structure and as the orientation requirements are complex, there can be errors in placement. Such placement errors can lead to extensive rework, which affects the progress of the project.

A key method to minimize errors is to train the personnel on the placement requirements. The preliminary works in this study shows that both physical modeling and computer based modeling are effective in training people before the start of the project. In comparing these 2 techniques, the physical technique has a slight edge, as it is natural for the people to use. However, in future as computer capabilities improve and people get more computer savvy, the advantage of physical model will reduce.

Acknowledgements

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AMT Co., Ltd., which was founded in November 5th 1998, possesses outstanding skills in designing, manufacturing and operating computer-based motion systems. In particular, the company is recognized as promising in business areas such as hydraulic system, robot using the servomotor system, automated construction machine and animatronics. In the company, the R&D team consisting of masters and doctors are independently carrying out the design and manufacturing of mechanic systems, controllers and programs and making ceaseless efforts to develop new technologies. AMT is performing R&D jointly with *Korea Institute of Construction Technology*, *Inha University*, *Hongik University*, and *Pusan National University*, etc. Although it is not large, AMT is making high profits in the market based on its strong technological power.

The main business areas of AMT are amusement, construction, system automation, and technical consulting. In the area of amusement, the company has developed 6DOF motion simulator adopting hydrostatics and servomotor system and, with it, is achieving a large part of the sales. In addition, the company developed large-sized animatronics robot and supplied it to major theme parks including *Everland*.

In the area of construction automation, AMT has just started the development and commercialization of tele-operated concrete pipe laying manipulator system, roadway sign painting and eraser system, etc.

100. Automation in Construction

The tele-operated concrete pipe laying system adopting 6DOF Stewart Platform is being developed jointly with *KICT* and *Inha University*. This research aims to develop a tele-operated concrete pipe laying manipulator and to generate the real-time as-built drawing of the pipe laid by integrating the developed system with CAD and GPS technologies. We have achieved the result of the research by proving that the tele-operated manipulator could improve working environment through eliminating works in trenches. Thus the research provides a solution to the issue of safety involved in piping in trenches. Moreover, as-built drawings generated from the newly developed system will contribute to the more efficient maintenance of pipe laying operation.

100. Automation in Construction

The picture above is the roadway sign painting/erasing robot system that AMT developed jointly with *Korea University* and *KIMM*. The erasing system, which has been researched together with *KIMM*, is under development adopting high-pressure water jet system. The prototype of the system will be completed and be developed into a commercial model until December 2004. The painting system developed by AMT in cooperation with *Korea University* was developed using Air Spray. The prototype of this system has been completed and is ready to be commercialized.

200. Amusement & Attraction

The amusement business is divided into two divisions; animatronics and motion simulator. Picture one and two show the appearance of big robots Hades (1) and Dragon (2) that are used in the final stage at 9:00 pm at *Everland*. Hades is six meters tall, which makes 17 kinds of motions and produces special effects including those using firing powder. It rises from six meters below the stage floor as the show starts (See the picture on Page 5). Dragon is 13 meters tall. It rises from four meters below the ground, making 12 kinds of motions and, after performing a show, disappears into the ground. The next page shows Dragon appearing from underground, unfolding its wings and long trunk.

Picture 3 is a motion simulator realizing virtual space. Various models are being manufactured, installed and operated, including those for one person, two, ten, fifteen and twenty.

200. Amusement & Attraction (Dragon)

200. Amusement & Attraction (Hades)

- Producing & setting up

- Going into action