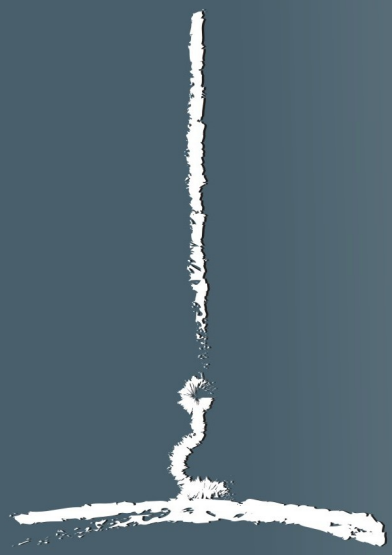


Automation and Robotics in Construction

24th International Symposium on Automation and Robotics in Construction

AUTOMATION AND ROBOTICS IN CONSTRUCTION

AUTOMATION AND ROBOTICS IN CONSTRUCTION

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PREFACE

The International Symposium on Automation and Robotics in Construction (ISARC) is the annual symposium of the International Association of Automation and Robotics in Construction (IAARC). It is a gathering of researchers, academics and practitioners interested in the use of information, computational and robotic technologies for planning, managing and executing construction projects. The first ISARC was held in Pittsburgh, USA in 1984. Since then the Symposium has taken place annually at various international locations.

The Indian Institute of Technology Madras is privileged to partner with IAARC to organise the 24th International Symposium on Automation and Robotics in Construction (ISARC 2007). The theme of ISARC 2007 "Appropriate Automation for Productivity Improvement" is particularly relevant to the construction environment of emerging economies such as India.

Until recently, automation and robotics in construction was not cost-effective in emerging economies. The key reasons were that the project requirements were undemanding, skilled labour was available and technology was expensive. Today, challenging project requirements and schedules coupled with a shortage of skilled labour and dropping costs of technology have made automation cost effective. However, in most situations, total automation is not the solution. The successful implementation of automation and robotics needs to achieve an appropriate human-machine balance to maximize productivity.

The areas covered by ISARC include all aspects of automation and robotics in the planning, design, construction and maintenance of the built environment. Papers submitted for ISARC 2007 has been organized into **five** themes-automated data collection, robotics and robot applications, information, and communication technology computational techniques and management of technologies in the construction context.

Automated Data Collection is an emerging area and technological changes are rapidly increasing the range of applications. Research reported in this area falls into two main categories - wireless and imaging technologies. The wireless technologies cover studies on RFID, mobile computing and ultra wide band for tracking, positioning and gathering information. The imaging technologies cover studies on applying LIDAR, infrared and stereo imaging to monitor projects.

Robot Technology and Applications has been a core area of ISARC since the inception of the symposium. Most of the papers in this proceedings fall into this category. The technologies addressed by the papers are: control algorithms for construction situations, mechanisms for earth moving and strategies for multiple manipulators. The application areas covered are: concrete paving, pavement inspection, paint spraying, ceiling glass installation and multi-purpose functions.

The papers in the area of *Information and Communication Technology* report on the customization and use of tools such as Computer Aided Design and Geographic Information System for site based decision support and project planning. A number of papers in this area also report work done in use of network technologies for design collaboration, data mining and knowledge management.

The *Computational Techniques* addressed by the papers focus on distributed optimization techniques such as agent-based modeling, swarm and ant-colony optimization, and genetic algorithms to solve various problems such as site-layout, resource scheduling, and design sequencing, In addition, several papers on the application of conventional optimization approaches to solve scheduling and planning problems are also included.

The final section of the proceedings contains papers related to *Management and Production* aspects. The papers in management aspects cover topics such as decision making and technology adoption. The production section contains papers on automating the production of construction materials such as earth plasters, fabrics and bamboo for cost effective construction.

The program for ISARC 2007 consists of plenary sessions and three parallel tracks. In addition to the key note lectures, the plenary sessions contained two panel discussions covering the areas of "Strategies for Appropriate Construction Automation in India" and "Developments in Automated Data Acquisition for Construction Projects"

The organization of this symposium and the publication of this proceeding would not have been possible without the support of many people and organizations. We are thankful to: the IAARC board of directors, Prof. M.S. Ananth, the academic patron of this symposium and Director of IIT Madras, Mr. K.V. Rangaswami, the industry patron and the President of Larsen & Toubro, India, Mr. Mohan Ramanathan, Managing Director, Advanced Construction Technologies, Chennai, for their contributions.

We are also thankful to: Prof. S. Mohan, Chairman of the organizing committee and Head, Department of Civil Engineering; our colleagues at the Building Technology & Construction Management Division: Profs. M.S. Mathews, A. Ramachandraiah, K. Ramamurthy, Ravindra Gettu, Manu Santanam; Prof. M.S. Shunmugam, Head, Department of Mechanical Engineering; our colleagues at the Manufacturing Engineering Section for supporting our efforts.

The publication of the proceedings required the assistance of many individuals. The thoroughness of Prof. K. Ramamurthy, Chairman Continuing Education, I.I.T. Madras was instrumental in bringing this as an IITM publication. The diligent effort of V. Senthil Kumar was critical to bring out the proceedings in the current form. In addition, the timely assistance of G. Kanagaraj, L. Boeing Singh, B. Kanagasabapathy and D. Sheeba were also important. We wish to thank all of them for their valuable inputs.

The collection of papers in the proceedings reflects the interdisciplinary nature of this area. We hope that the proceedings will inspire a new generation of researchers to pursue research along these exciting avenues.

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N. Ramesh Babu
K.N. Satyanarayana
K. Ananthanarayanan
Ashwin Mahalingam
Uma Maheswari

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TUCKER-HASEGAWA AWARD LECTURE

Prof. Carlos Balaguer
Robotics Lab,
University Carlos III of Madrid

24th International Symposium on Automation & Robotics in Construction (ISARC 2007)
Construction Automation Group, I.I.T. Madras

TOWARDS ROBOTIC SMART HOMES

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ABSTRACT

The nowadays smart homes try to move from conventional remote-controlled houses to intelligent environments. The focus has been made in blending high-tech computing into the home environment and in substituting the interaction with a box on a table by different friendly & intelligent HMI devices. Nevertheless, the introduction of real robots in home environment isn't treated yet. How will be the new smart homes with robots moving among their inhabitants? This type of homes, called robotic smart homes, will be very different of the conventional smart ones. The paper deals with the state-of-the-art of personal home robots and with the homes design in which these robots will move. One of the key issues is the analysis of the nowadays home space and the adaptation of the robots' locomotion system for them. Several types of robots (mobile, climbing and bipedal) together with the new home and rooms structure have been analyzed, together with the smart homes control system.

KEYWORDS

Smart Homes, Personal Robots, Apartments Design, Human-Robot-Home Interaction

1. INTRODUCTION

The new generation of the personal home robots is coming. Most of studies show that we are in the beginning of the new mass production robotics industry. Robots will leave the factories and will enter at homes. But are the homes prepared for these robots?

The adaptation of new and existing homes for this change is one of the crucial challenges of the robotics and construction research communities. The existing smart homes concepts need to be revised in order to admit free moving robots in daily living environments.

2. SMART HOMES

The nowadays smart homes try to move from conventional remote technology to intelligent environment (ambient) through ubiquitous computing. The research efforts are focusing in four basic elements: ubiquity, awareness, intelligence and natural interaction (as declare Mrs. Harmke de Groot from Philips Electronics).

Ubiquity refers to a situation in which people are surrounded by multiple interconnected embedded systems, which are invisible in their environment. Awareness means the ability of the system to locate and recognize objects and people and their intentions, while intelligence involves a digital surrounding being able to analyze the context, adapt itself to the people who live in it and learn from their behaviour. Natural interaction, finally, relates to advanced modalities such as natural speech and gesture recognition, as well as speech synthesis, which could enable a much more human-like communication in a digital environment than is possible today.

In this context, the biggest EU project on ambient intelligent entitled AMIGO (Ambient intelligence for the networked home environment) was lunched in 2004 till 2008 [1]. This project, with consortium of 15 European companies and 24M€ budget, has the objective of research and develop open,

standardized, interoperable middleware and intelligent user services for the networked home environment, which offer users intuitive, personalized and unobtrusive interaction by providing seamless interoperability of services and applications. Several demonstration domestic scenarios, formed by living room, bedroom, kitchen, bathroom, etc., had been selected in order to verify the developed technologies (Fig. 1).

The Philips' HomeLab, located in Eindhoven, is built as a two-storey house with a living, a kitchen, two bedrooms, a bathroom and a study. At a first glance, the home does not show anything special, but a closer look reveals the black domes at the ceilings that are hiding cameras and microphones (Fig. 2).



Figure 1 EU AMIGO's Demonstration Scenario [2]



Figure 2 Philips HomeLab [3]

Other well known smart homes experiments are: 1) the GeorgiaTech's Aware Home that has audio note system, automatic blinding and lights system, gray water recycling, everyday home assistant, memory aids, etc. (Fig. 3) and 2) the MIT House_n with the mission to conduct research by designing and building real living environments - "living labs" - that are used to study technology and design strategies in context.



Figure 3 GeorgiaTech's Aware Home's Living Room [4]



Figure 4 MIT House_n's Kitchen [5]

3. HOME PERSONAL ROBOTS

Service robots become to be but reality that dream. Experts predict that the next hot field will be home personal robotics. According to Bill Gates "I really have in mind … the emergence of the robotics industry, which is developing in much the same way that the computer business did 30 years ago. I can envision a future in which robotic devices will become a nearly ubiquitous part of our day-to-day lives. … We may be on the verge of a new era, when the PC will get up off the desktop and allow us to see, hear, touch and manipulate objects in places where we are not physically present." [6].

In the same way, the European Robotics Network (EURON) roadmap identifies the high priority of personal robots in home: “In the next future, in a 20/25-year perspective, domestic, chore activities are expected to be something about which we will have to worry less and less. Two trends can be easily identified: The homes themselves will become more intelligent in terms of sensors and interconnecting processing units, and they will be populated by robotic servants that operate in these intelligent houses in close interaction and cooperation with the human user.” [7].

It is possible to classify the home personal robots in three gruops depends on the locomotion system they used:

1. wheeled driven mobile robots; beginning by the market successful cleaning robot Romba by iRobot (Fig. 5) [8] and finishing by the ARMAR domestic servant developed by University of Karlsruhe in Germany (Fig. 6) [9];
2. biped humanoid robots; the most advanced one is the Japanese HRP-2 able to walk and help humans in domestic environments (Fig. 7) [10];
3. climbing assistance robots like ASIBOT that helpselderly and disease people in daily tasks like washing, tooth cleaning, shaving, make-up, etc.; the robots can able to climb in the walls and ceilings (Fig. 8) [11].



Figure 5 iRobot’s Romba Home Cleaning Robot



Figure 6 ARMAR Wheeled Home Robot



Figure 7 HRP2 Biped Humanoid Robot



Figure 8 ASIBOT Climbing Assistive Robot

4. HOME SPACE VS MANOEUVERING

It is clear that the home environment strongly influence on the mobility of the robots. If you have common home furniture distribution (Fig. 9) there are some areas where the robots have difficulties to move. Moreover, some areas will not accessible at all for some kind of robots.

Wheeled based mobile robots, except small dives like cleaning robots, have tremendous difficulty to move in even no cluttered domestic layout (Fig. 9). They haven't enough space to manoeuvring and can access only to the small part of the home. Only some omnidirectional wheel drives permit better manoeuvring, but its cost and complexity are very high. In general, the wheeled platforms are commonly big and non-holonomous.



Figure 9 Common Home Layout (by SmartDraw.com)

On the other side, are the bipedal humanoids that have better manoeuvring, like the humans, but have very complex stability posture control. The advantage of use robots like us in the environments design for us is clearly very big. The main drawback is the cost of this type of systems, taking in mind that most of them aren't commercial products now.

Finally, the robots which use walls and ceiling to move have a big advantage. Moving robot from one docking station to another in the wall avoid the collision with the floor standing furniture. The space used to move is commonly very empty (see the ceiling) and robots have the aces to most of the home space. In some configuration the robot is able to one room to another. The main disadvantage is the complex control against the gravity and the security of good grasping to the wall [12].

5. ROBOTIC SMART HOMES

As it was discussed, the robot locomotion system and home design have very close relationship. The development of new type of robotic smart homes needs some restrictions and improvements in the construction process. Some of them are:

1) Reinforce home's walls and ceiling to be able to support the weights of the robot and their transferring structure (Fig. 10). This reinforcement doesn't need to be very expensive and complex. It is possible to use, for example, light steel frame structure [13] and not in the entire home only in the robot action areas.



Figure 10 Home Personal Robot in the Ceiling

2) Introduce the embedded power supply system in the walls and ceiling in order to be prepared to install docking stations in the environment (Fig. 11). This wall embedded system can also be used to the communication purpose, i.e. to communicate with the central smart home computer and the distributed sensorial system. This leads to new generation of embedded wall's panels which include not only sensors and communications but also power supply, generally low amp.

3) To don't excessively increase the home's price, the architectural design and used materials must be as common as possible. This is why, we suggest some design modifications

like wider doors and corridors, rounder corners, slightly higher ceilings, etc. Although suggested robots can move more a less freely in the home environment, wider space is necessary (Fig. 12).



Figure 11 Home Assistive Robot in the Wall

Improve the smart home's communication, sensorial and processing systems in order to incorporate in the system's architecture the robot home controller. The control architecture based on the distributed concept is the most adequate one.



Figure 12 Humanoid Robot Walking in the Room

6. CONCLUSIONS

The analysis of the robot smart homes had been made. It is clear that robotics devices in home introduce new concept of home design and also new materials, new design restrictions and new potential applications.

The control system of the home needs to be improved beyond the actual smart homes control architectures. The integration of the robot controller, under distributed concept, the sensorial system (vision, proximity, temperature, etc.), the distributed DBs and the home controller are the key issues.

The new robotic smart homes will provide higher quality of live for the families. Specially for elderly, disease and childs. Home robots will be the new domestic appliance but with the possibility of moving around us and interact with us.

7. ACKNOWLEDGMENTS

The author wants to thanks all the members of the RoboticsLab for their help and support, and specially the research teams of the ASIBOT, Rh-1 and ManuBuild projects. Finally, thanks to CICYT, IMSERSO and EU for sponsoring our projects.

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AUTOMATED DATA COLLECTION

24th International Symposium on Automation & Robotics in Construction (ISARC 2007)
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AUTOMATED GEOREFERENCED USER POSITION TRACKING FOR CONTEXTUAL INFORMATION RETRIEVAL ON CONSTRUCTION SITES

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ABSTRACT

This paper presents research that is evaluating the capability of an automated location-based methodology in identifying and retrieving contextual project information on indoor and outdoor construction sites for supporting decision-making tasks of site personnel. Under this methodology, construction entities visible in a user's field of view at any given time and location can be identified and cross-referenced with corresponding design and "as-built" data residing in construction databases and management information systems. The presented research attempts to achieve this by integrating outdoor positioning technologies together with location-based wireless technologies. Outdoor positioning techniques have been investigated and validated in other research efforts [1] [2] through the use of Global Positioning System (GPS) receivers and magnetic orientation tracking devices. For indoor environments, this paper aims at identifying Wireless Local Area Networks (WLAN) indoor positioning technique, a cheap, easily deployable and universally compatible location system for indoor use.

KEYWORDS

Context-aware Computing, WLAN, GPS, Tracking, Information Retrieval

1. INTRODUCTION

Field construction tasks such as inspection, maintenance, progress monitoring, and others require access to a wide range of project information. While working on construction sites, site engineers, inspectors and other site personnel currently have to spend a lot of time in manually searching into piles of papers, documents and drawings to access the information needed for important decision making tasks [3]. Such lost time amounts to lost productivity, and thus lost money. There is therefore a clear need for a new methodology that can allow rapid identification and retrieval of contextual project information for productivity improvement on construction sites.

The objective of this paper is to describe the automated GPS and WLAN based methodology that is being proposed in order to improve productivity on construction sites while minimizing the time, cost and effort currently needed for contextual project information retrieval process. Proof-of concept experiments were performed outdoors on a building structure at the University of Michigan as well as indoors in one of the laboratories. The objective was to evaluate, given users' location and head orientation, the extent to which objects visible in a user's field of view can be dynamically identified and continually tracked. The obtained results highlighted the potential of using location-aware technologies for rapidly detecting contextual objects.

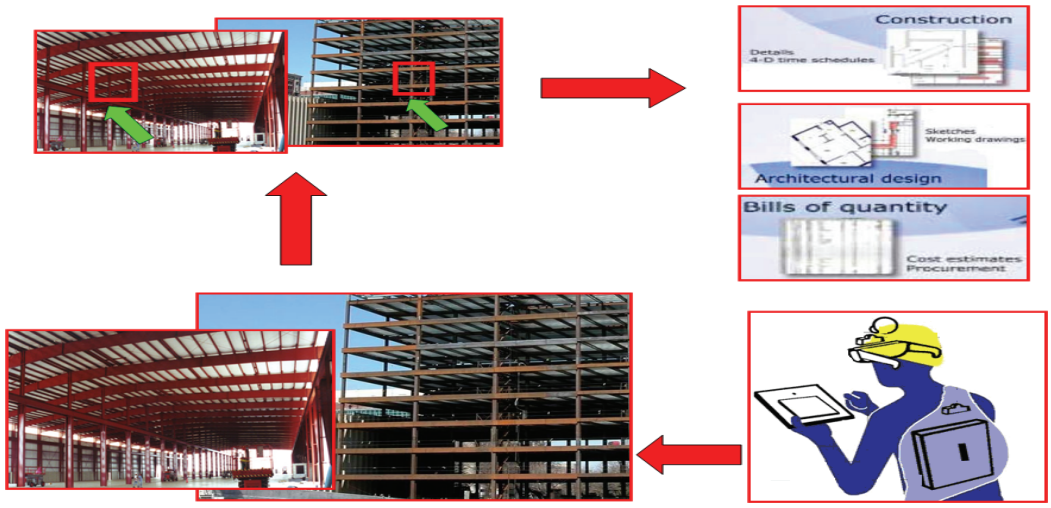


Figure 1 Proposed Location-Aware Information Retrieval Methodology

2. PROPOSED LOCATION-AWARE METHODOLOGY

In this paper, the authors are researching the requirements of a location-aware based methodology that focuses on automatically retrieving contextual project information for on-site decision-making on construction sites. Figure 1 summarizes the mechanics of the proposed framework.

2.1. User Position Tracking in Outdoor Environments

For outdoor applications, positioning techniques have been investigated and validated in recent work by our research group [1] [2]. The outdoor positioning technologies were integrated within an outdoor AR platform (UM-AR-GPS-ROVER). The hardware configuration consists of a geo-referencing based algorithm developed using Global Positioning System (GPS) receivers and magnetic orientation tracking devices to track user's dynamic viewpoint. A mobile user equipped with UM-AR-GPS-ROVER hardware is shown in Figure 2.

Using the aforementioned outdoor positioning tools, a preliminary proof of concept experiment was performed to validate the proposed georeferenced information retrieval methodology (Figure 3).

It was conducted at the G.G. Brown (GGB) building at the University of Michigan and the objective was to identify the different zones of the building (i.e. the Civil and Environmental, Mechanical and Dow sections) as the user navigates around the building and observes the different segments. At all times during the experiment, the user's position and orientation were tracked by the GPS and magnetic tracker and the designed algorithm was executed to automatically interpret which portion of the building the user was inspecting at a particular time. The identified components were retrieved from a 3D CAD model of the building and were presented to the user interactively. In fact, given the near and far distances as well as the field of view angles, the eight coordinates of the truncated pyramid (i.e. viewing frustum) are computed [4].

Then the viewing frustum is aligned with computer representations of objects (i.e. building structure) that exist in the space the user is navigating in. In this case, a 3D VRML model of GGB's external shell is registered at the known outdoor location. In order to interpret which entities in the environment are visible to an on-site user at a given instant, an interference analysis technique known as raycasting [5] is used. Raycasting (Figure 4) was implemented, using a simple method to determine the intersection between a ray (virtual line segment originating from the user) and a polygon in 3D (the building model in this case).



Figure 2 Outdoor Hardware Prototype

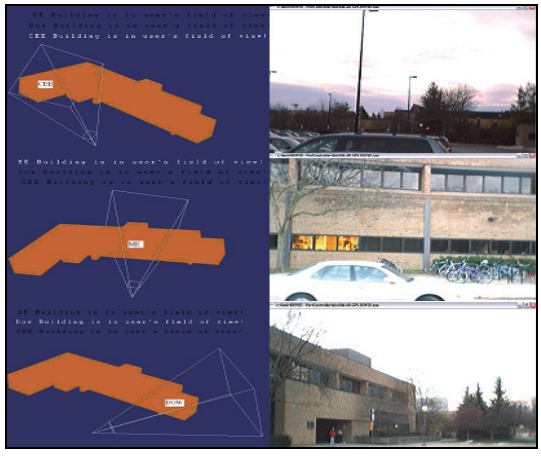


Figure 3 Virtual (i.e. Computer Interpreted) and Corresponding Real Views of G. G. Brown Laboratory Building



Figure 4 Identifying Contextual Objects with Raycasting

Each time the user moves on the site, the intersection between the rays and the object of interest (designed entity) is computed and interference detection is reported [6].The obtained results indicated a near perfect match between the real building components in the user's view at a particular time and the corresponding CAD components that were retrieved based on the proposed methodology.

2.2. User Position Tracking in Indoor Environments

In the case of indoor applications, GPS technology is not suitable because it becomes less accurate when there is no continuous straight signal path between the satellite and the receiver. Therefore, there is a need to investigate feasible techniques of user position and orientation tracking in indoor enclosed environments. WLAN technologies are being studied as a possible indoor location-based technique to be integrated in the proposed methodology (Figure 5).

This technique is based on the estimation of the location of the Mobile User (MU) by combining measurement signals (Signal Strength SS) from a number of Access Points (AP's) situated at known locations in a building as shown in Figure 5.

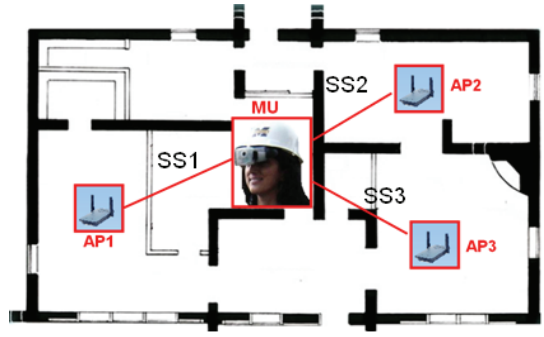


Figure 5 WLAN-Based Approach

Recent work by [3] developed a prototype application for context-aware information delivery that relies on the Ekahau position tracking system [7]. A technology similar to that adopted in the Ekahau system offers the best promise for this research study. Ekahau is a software-based real-time location system that can easily integrate with

WLAN networks and identify the location of tracked objects within a few meters (Figure 6).

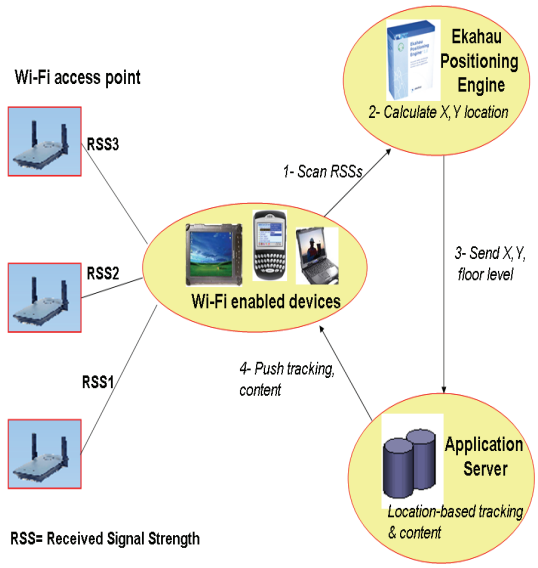


Figure 6 Ekahau Positioning Engine Mechanism

The positioning engine tracks the real time position of a WLAN-enabled mobile device. It discovers all the WLAN-enabled devices using their IP addresses, and makes use of the signal strength measurements as detected by the access points to determine the actual position [3]. Based on this system, another preliminary experiment was also conducted indoors at GGB in the Construction Laboratory. The objective was to identify the position (X, Y and floor level) as well as the head orientation (pitch, roll and yaw) of a mobile user as he is walking inside the lab (Figure 7, 8).

3. CONCLUSION

This paper presented the overall architecture of a georeferencing based automated methodology for identifying and retrieving contextual project information on indoor and outdoor construction sites for supporting decision-making tasks of site personnel.

In order to demonstrate the feasibility of the proposed research, a proof of concept experiment was first conducted in an outdoor environment. A user equipped with a GPS receiver and magnetic

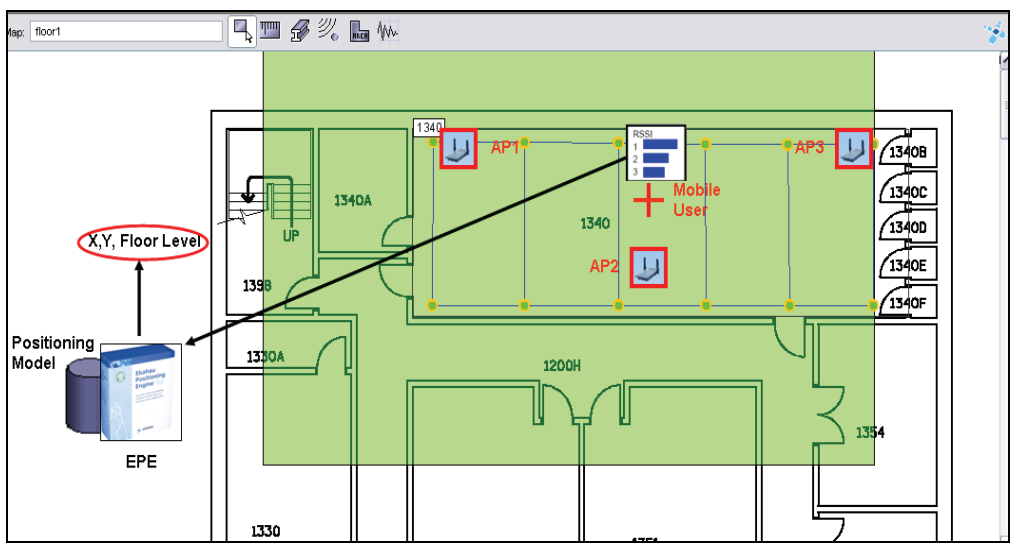


Figure 7 Ekahau Calibration in GGB (Construction Lab, Room 1340)

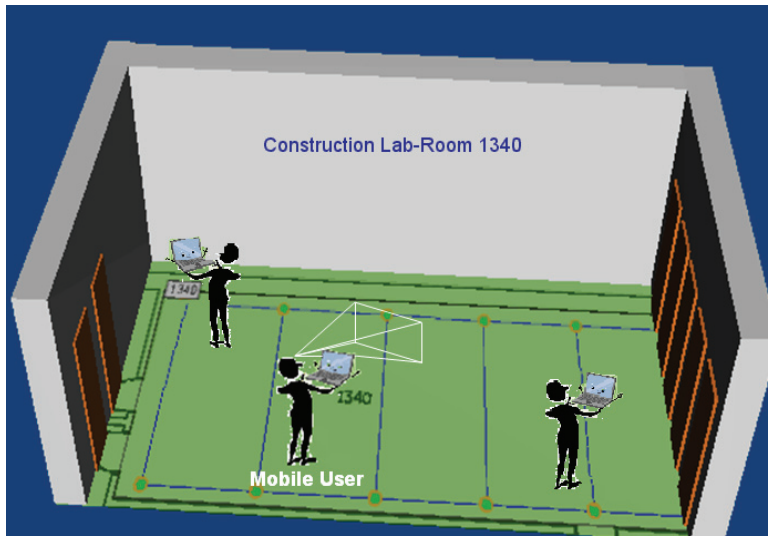


Figure 8 Virtual Representation for Different User's Positions and Orientations Inside the Lab

orientation tracker inspected the segments of the GG Brown laboratory building at the University of Michigan. The obtained results highlighted the potential of using location-aware technologies for rapidly identifying and retrieving contextual information for on-site decision making tasks in construction and other fields. Another proof of concept experiment was carried out in the Construction Laboratory of the Civil Engineering Department at the University of Michigan. The results highlighted the potential of using indoor technologies to identify the position (X, Y and floor level) and head orientation of a mobile user as he is walking inside an enclosed space.

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ULTRA WIDE BAND (UWB) BASED PRECISE POSITIONING SYSTEM FOR ROBOTICS

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ABSTRACT

The advent of the Global Positioning System (GPS) provided reliable and accurate position information worldwide for outdoor environment. However, many applications are emerging where position information is required and the environment or complexity considerations prohibit the use of GPS. As a result, areas as diverse as robotics, sensor networks, and ubiquitous computing have seen an increase in research in indoor position determination systems. While the majority of current work relies on laser, ultrasound, or narrowband RF for positioning, such techniques are severely limited in harsh environments with significant multipath and/or interference. In this paper we discuss the features of Ultra Wideband-Band (UWB) precise position system because of its usefulness in harsh environment, its ability to fuse accurate position-location with low-data rate communication, and its covertness for tactical applications. This paper presents the system design options for UWB based positioning systems, and shows how they match the indoor location demands of emergency services. This paper also presents the analysis of UWB RF Channel performance as a function of the major parameters, including bandwidth, frequency component spectral spacing, transmitted signal power, and range. These results facilitate the design of UWB positioning systems for specific environment.

KEYWORDS

OFDM, Impulse Radio, TDOA, PSD, CRB

I. INTRODUCTION

There has been a growing need for wireless systems that provide accurate position location. For example, indoor positioning to track personnel or assets in laboratories, robots, warehouses, and hospitals is becoming popular. Applications of wireless positioning for search-and-rescue operations by military commanders and fire fighters have become important because of increasing interest in security services.

2. OVERVIEW: UWB

Ultra Wide Band is a new technology, which has been recently introduced for wireless communication systems. The UWB signal is defined as any signal, which occupies a bandwidth larger than 500 MHz, or has a fractional bandwidth greater than 0.20. Due to its large bandwidth, an extremely fine time resolution (i.e. range resolution) can be achieved and consequently, this provides good potential for application in ranging and positioning.

UWB signaling consists of two different formats: the first is impulse radio (IR) that uses high bandwidth analog baseband pulses to carry information. The second is a multicarrier approach which relies on orthogonal-frequency-division-multiplexing (OFDM), with multiple subbands across the UWB spectrum. The multi Carrier signal structure used in an Orthogonal Frequency Domain Multiplexed (OFDM) signal consist of many sinusoidal subcarriers. Such a signal

structure has a major advantage over the ultra wideband signals that are often proposed for performing precision location in high multipath environments, as it is easily adapted to conform to existing spectral allocations. This technique is also well suited for use on ad hoc wireless networks, allowing precise determination of locations of wireless nodes with respect to one another.

3. CONVENTIONAL POSITIONING OF ROBOTS

Robotics is an area which has had much success over its many years of existence. Mobile robots consist of many sensors to discover their environment and use the information about their environment for adaptation. Infrared and ultrasonic sensors are examples of such sensors.

The infrared signal has the same properties as visible light. It cannot pass through walls or obstructions; therefore, it has a rather limited range in indoor environments. However, the propagation speed is high, approximately 3×10^8 m/s. Thus, it requires more sophisticated circuitry than ultrasound signals. Indoor lighting interferes with this type of signal and causes problems in accurate sensing. It generally has a rangeof around 5 m. The infrared devices are usually small in size compared to ultrasound devices .

Ultrasonic transceivers, traditionally, are mounted with a transmitter and a receiver. The transmitter emits a ping (sound burst) which bounces off the nearest object and the receiver is always 'listening' for the return signal. Using a microcomputer with a built in timing device to detect the time of flight, it is possible to calculate the range of the object relative to the ultrasonic sonar. Ultrasonic transceivers have been used in position determination of robots because of their availability and cost. The ultrasonic position measuring system makes use of triangulation theory to determine the position of the transmitter (mounted on the robot) with respect to the known positions of the multiple receivers.

One of the clear downside of ultrasonic transceivers is the fact that air coupled ultrasound typically operates based on mechanical systems. Therefore, they become more sensitive to environmental impacts.

A single ultrasonic sensor element has a maximum of 180 degrees directivity pattern. Hence, more than one sensor element is needed for whole space coverage. Besides, a single ultrasound sensor pattern has a wide beam. Hence, an array consisting of several ultrasonic elements is necessary for more narrow beams. Moreover, ultrasonic waves are acoustical mechanical waves. Therefore, polarization of the received waves cannot be used to differ between direct received waves and indirect ones due to reflections.

4. POSITIONING WITH UWB

The radar community has been using signals similar to UWB pulse signals for ground-penetrating radars for many years. The reason why a communication scheme using narrow pulse signals has been proposed is because of their novel properties which possess advantages over conventional narrow-band or wide-band signals. First, range resolution is extremely fine, which provides a good potential for the applications in ranging and positioning.

The power spectral density of UWB systems is generally considered to be extremely low, especially for communication applications. The power spectral density (PSD) is defined as

$$PSD=P/B.$$

Where P is the power transmitted in Watts (W), B is the Bandwidth of the signal in Hertz (Hz) and the unit of PSD is Watts/Hz (W/Hz). Historically wireless communications have only used a narrow bandwidth and can hence have a relatively high power spectral density.

We know that frequency and time are inversely proportional, sinusoidal systems have narrow B and long time duration t. For a UWB system the pulses have a short t and very wide bandwidth (B). The energy used to transmit a wireless signal is not infinite and, in general, should be as low as possible, especially for today's consumer electronic devices. If we have fixed amount of energy we can either transmit a great deal of energy density over a small bandwidth or a very small amount of energy density over a large bandwidth.

For UWB systems the energy is spread out over a very large bandwidth (hence the name Ultra Wide Band) and, in general, is of a very low power spectral density. The major exception to this general rule of thumb is UWB radar systems which transmit high power over a large bandwidth. However, here we will restrict ourselves to the communications area.

UWB signal supplies the high bandwidth at a lower center frequency, which is advantageous for penetration of materials and for operation in shadowed environments. Resolvable multipath and the penetration capability enable UWB radio applications in complex multipath environments, including indoor wireless local area network (LAN). Furthermore, the absence of a sinusoidal carrier may allow simpler radio architecture because simply no intermediate frequency (IF) stage is necessary.

5. MC-UWB SYSTEM FOR POSITIONING

In UWB based positioning system, Multi Carrier (MC) techniques can efficiently combat frequency selective fading. Such robustness in presence of frequency selective fading is very useful, especially for applications involving high data rate. One of the problems with a single carrier signal structure is that as the symbol rate increases the symbol interval becomes shorter than the delay spread. A Multi Carrier signal structure solves this problem by decreasing the symbol rate and increasing the number of carriers. The basic idea behind the OFDM signal is to take a signal and send it over multiple low rate carriers instead of a single high rate carrier.

An OFDM signal consists of many sinusoidal subcarriers. These subcarriers are orthogonal and therefore do not overlap with each other. The advantages of using a Multi Carrier signal structure are listed below:

- Improved spectral efficiency
- Robust in fading environment
- Simplified equalization needed
- High data rate can be achieved
- Signal generation is simple

The structure of the OFDM signal proposed is of the form:

$$Sc(t) = \sum_{m=0}^{M-1} A_c e^{2\pi j\,(fo + m\Delta f)\,t + \Phi m}$$

Where M is the number of sinusoidal carriers with frequency spacing Δf and each carrier has arbitrary phase Φm. The signal proposed occupies a very wide bandwidth but each subcarrier occupies a very low portion of the total band and hence it is also called Multi band Ultra wideband (MB-UWB).

6. POSITION LOCATION ALGORITHM (TDOA) FOR MC-UWB

The proposed precise positioning system uses this MC-UWB signaling technique. The system uses four or more receivers to calculate a three dimensional position of the transmitter. The position location algorithms are based on Time Difference of Arrival technique (TDOA).

For the case of real signals, is described as follows the signal structure

$$S(t) = Sc(t) + Sc^*(t) \quad (1)$$

$$Sc(t) = \sum_{m=0}^{M-1} A\,Cos(2\pi\,(fo + m\Delta f)\,t + \Phi m) \quad (2)$$

equation in terms of the sampled signal system as $\Delta f = K\delta f$ and $fo = Mof$, where $\delta f = fs/N$ is the DFT frequency sample separation.

$$S(t) = \sum_{m=0}^{M-1} A\,Cos(2\pi\,(Mo + mK)\,\delta f\,t + \Phi m) \quad (3)$$

If this signal is received at reference sites, with distances d_k from the source giving rise to propagation delays $\tau_k = d_k/c$, then each carrier component is shifted by a phase shift which depends both upon τ_k and the carriers frequency.

In equation (3) it may be noted that if the reference sites have synchronized clocks and the source clock has some unknown offset, this offset induces another unknown phase shift dependent on to carrier index. Let's now assume that the sampled received signal at the k_{th} reference is of the form

$$\Psi_m = 2\pi\,(fo + m\Delta f)\ to$$
$$\text{for } n = 0 \ldots N\text{-}1 \text{ with DFT}$$
$$r_k(n) = s_k(n)+n_k(n)$$
$$R_k(n) = S_k(n)+N_k(n) \quad (4)$$

The phase difference between adjacent carriers for the signal

The phase difference between adjacent carriers for the signal received at reference node k, S_k (M_o+ mK) for $m = 0 \ldots M$ -1, corrected for the known phases Φ_m satisfies

$$\Delta\theta_k = \Phi_{mk} - \Phi_{m-1,\,k} - \Phi_m + \Phi_{m-1}$$
$$= -2\pi\Delta f\,\tau_k + \Psi_m - \Psi_{m-1}$$
$$= -2\pi\Delta f\,\tau_k + m\Delta\Psi \quad (5)$$

Finally, the difference of the phases obtained as above for carrier m at two sites, q and r, is $\theta_{qr} = \Delta\theta_r - \Delta\theta_q$, from which we can recover the Time Difference of Arrival (TDOA) of the signals at those sites,

$$\Delta\tau_{qr} = -\,\theta_{qr}/2\pi\Delta f = (d_2 - d_1)/c \quad (6)$$

in which c is the velocity of the wave in our medium. by choosing Δf sufficiently small, we can make our TDOA solution unambiguous throughout a ranging cell which is defined by the locus of points within distance $R = c/\Delta f$ of any receiving site with respect to the particular robot.

7. CRAMER RAO BOUND FOR FREQUENCY ESTIMATION

Cramer and Rao suggested a lower bound on estimation of the delay accuracy (which reduces to the ranging accuracy) based on the bandwidth and the SNR of the received signal, often called Cramer Rao lower bound (CRLB).

The problem of estimating the frequencies of multiple, arbitrarily spaced, sinusoidal signals from a noisy linear combination provide an expression for the Cramer Rao Lower Bound (CRLB) for estimation of the frequency coefficient $\Delta\theta_k$, which expressed in terms of variables defined above, is

$$E\,\{\Delta\theta^2_k\} = (6/M^3)\,\sigma^2_n\,/|c_1| \quad (7)$$

where σ_n is the standard deviation of the additive white Gaussian noise (AWGN) associated with each frequency sample and c_1 is the amplitude of the complex sinusoid formed by the frequency sample values. CRB given in terms of total received power (P_s), total noise power (P_n) by

$$E\,\{\Delta\theta^2_k\} = 12\,P_n/M^2\,NP_s \quad (8)$$

since the time delay associated with the phase progression parameter is given by

$$\tau = \Delta\theta/2\pi K\delta f = N\Delta\theta/2\pi K f_s \quad (9)$$

We can write the CRB bound for the variance of the time estimates as

$$\sigma_\tau^2 = 3NP_n/\pi^2\,K^2 f_s M^2\,P_s^{\,2} \quad (10)$$

In the case of a heterodyne receiver in which a sub-band of width B Hz is sampled at rate $B = 2f_s$ for a time window of $T = N/2B$

$$\sigma_\tau^2 = 3N_o/8\pi^2\,B^2\,T\,P_s^{\,2} \quad (11)$$

8. CRB FOR POSITION ESTIMATION AND RECEIVER SIDE COMBINED LOCATION PERFORMANCE FOR ROBOTS

A. Position Estimation

An estimate is obtained by combining the Cramer Rao Bound for the Time Difference Of Arrival (TDOA) estimate and the multi-carrier signal for positioning of robots. This expression was used to perform validation of our position estimator subsystem.

We can now combine the results of the last two sections to obtain the performance of the locator with respect to received signal characteristics. Furthermore, we will substitute particular sensor geometry into the equation in order to obtain a simple parameterized model.

Where in six sensors are used, three placed in the z=0 (ground level) plane in a triangle comprising the origin and two points *w* meters offset in the x and y directions from origin. The remaining three sensors are each *h* meters above the first set. Likewise, we fix the position of the robot at approximately *w* units from all the sensors, that is, essentially at the far corner of the cube, three sides of which are defined by the sensors. Inserting this geometry in equation (11) we can obtain CRB for the time of arrival estimation of positioning

$$\sigma_r = \frac{C\sqrt{6N_o}\sqrt{5h^2+2w^2}}{8\pi\sqrt{P_s}^2 T B h} \quad (12)$$

B. Receiver Combined RF Channel Performance

The performance of the RF channel over which these signals transit can be calculated using Friis formula. The Friis Transmission formula expresses the received power (P_s) in terms of the transmitted power (*Ptr*), the antenna gains etc.:

$$P_s = \frac{P_{tr} G_{tr} G_{rec} \lambda^2}{16 \pi^2 r_o^2} \quad (13)$$

in which r_o is, as before, the distance from the target to the various sensors, and G_{tr} ,G_{rec} are the transmitting and receiving antenna power gains, respectively. If we take the antennas to be omni directional, then the antenna gains both become unity and may be omitted from the following equations. Finally, λ is the wavelength of the RF signal in meters.

Given a received signal with a noise figure (*NF*) and antenna temperature of T_a degrees Kelvin, then we can express the noise power spectral density of the received signal as

$$N_o = 4 K_B T_a 10^{NF/10} \quad (14)$$

where K_B Boltzmann's constant. We can now substitute these expressions for the noise power density and the received signal power into our earlier equation for the estimated standard deviation of location error. The particular geometry of target and sensor chosen before, omnidirectional antennas, a front end noise figure of 3 dB, antenna temperature of 290 K and a wavelength equal to the shortest wavelength in the signal (hence worst case attenuation, that associated with *f max*). With these substitutions we obtain

$$\sigma_r = \frac{38\times10^{-8}\sqrt{5h^2+2w^2}\ f_{max}\ w}{B\ h\ \sqrt{Ptr.T}} \quad (15)$$

This can be further simplified by noting that $E = Ptr.T$ is the energy in each period of the transmitted waveform and that $F = B/f_{max}$ is the fractional bandwidth of the signal. Thus, for the case under study:

$$\sigma_r = \frac{38\times10^{-8}\sqrt{5h^2+2w^2}\ w}{F\ h\ \sqrt{E}} \quad (16)$$

Remarkable aspect of this result is that performance is not directly a function of the number of carriers used or the band in which these carriers are deployed, or the speed of the signal in its medium (c), but rather only of the geometry, the fractional bandwidth of the signal and the energy per signal period. Also remarkable is the high precision that can be achieved with relatively modest power levels and fractional bandwidths if the sensors and target are closely co-located. This is best seen by generating a system design graph from these equations which targets a given performance level.

We have a graph that relates the required values of *w,* with different values of *E* and *F* for the case of a robot location standard deviation of 10 cm and a height separation of sensors of 5 meters. The above analysis and simulation results can be used to construct precise positioning systems for robotics.

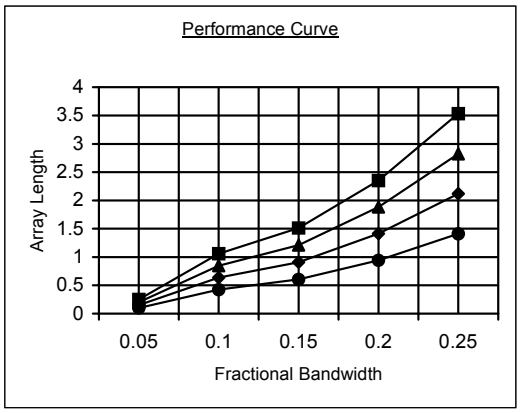


Figure 1 Performance curve generated from the design equations for the 6-sensor geometry targeted location with different transmitted signal power level

9. CONCLUSION

In the robot positioning system, performance analysis as a function of transmitted signal power and bandwidth and system geometry has yielded encouraging results and has produced performance equations, which can be used for design of positioning systems to achieve desired performance levels. For future work, we would like to investigate ranging in multipath environments. This is a major limiting factor in location determination using GPS in urban areas or indoors. A novel aspect of UWB ranging is the capability to detect the direct path signal accurately using the fine time resolution of an UWB signal.

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RAPID AUTOMATED MONITORING OF CONSTRUCTION SITE ACTIVITIES USING ULTRA-WIDEBAND

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ABSTRACT

Monitoring construction site activities is a critical concern to most stakeholders (owners, contractors, architects, engineers, suppliers, etc.) in a construction project. Successful projects are often determined by the level of awareness of project status or work task performance. Thus, information has inherent value for real-time or near real-time decision making. Good resource procurement and resource allocation of workforce, material, and equipment comes in play when job site conditions can be efficiently and effectively assessed. Semi- or automated technologies in the data collection and assessment process can assist in making fast and confident decisions. This paper introduces an emerging technology called Ultra Wide Band (UWB) for real-time location sensing and resource tracking. The technology, its use as data collection tool, preliminary data processing algorithms, experiments, and results are presented in the context of active work zone safety and material location tracking. Many more application areas exist where UWB might impact the field and project management level to overall benefit the construction industry's competitiveness.

KEYWORDS

Ultra-Wideband, Real-time, Sensing, Monitoring, Tracking, Emergency Response, Safety, Productivity

1. INTRODUCTION

Technological advancement in other industries strives for fast data collection and processing to enhance the flow of resources and to minimize logistical efforts. An example is the sophisticated tracking and progress monitoring of products during manufacturing and warehousing. In construction, however, adaptation or development of technologies last longer due to often required return on investment and benefit-risk analysis. Although this paper does not address the reasons of why few technologies get implemented in construction, it concentrates on how emerging technologies can help solve some of the problems construction field personnel face every day. The need for innovative technologies in construction becomes necessary when, for instance:

(1) Contacts resulting from struck-by events of heavy equipment and many other equipment related accidents need to be avoided. Thus, designing active safety tools is a particular application in construction that requires fast updates of machine location and its surrounding object positions in space.

(2) Resource tracking in the entire supply chain during construction and the life-cycle of the built environment to improve efficiency and effectiveness to overall benefit the construction industry and society.

Many different technologies have the potential to become a key element for solving these and other problems. In particular faster data acquisition and processing tools in construction are needed that allow real-time location detection and tracking of resources.

This paper provides a brief overview of recent technological innovations in construction resource tracking and progress monitoring, discusses the requirements of Ultra Wide Band technology that is needed for specific construction applications, and examines a few experiments conducted with the UWB systems in the construction field and inside the Real-time Automated Project Information Decision Systems (RAPIDS) research laboratory. Preliminary experimental results will be presented in the context to construction site resource location tracking and active safety. Finally, an outlook of future work ahead is provided.

2. BACKGROUND

In the last decade a number of reasons increased the interest in locating the position of resources. Worldwide competition, tighter schedules, and shrinking budgets demanded more accurate performance of work at an increased overall level of productivity. These drivers made the construction industry to adapt technologies such as Global Positioning System (GPS), laser tracking, and recently to support the development of active Radio Frequency Identification (RFID) in combination with GPS [1, 2]. Other semi-automated technologies, such as time-lapse photography in combination with a priori Computer Automated Design (CAD) information allow monitoring progress on construction sites [3].

A technology that might have answers for real-time locating systems is Ultra Wide Band (UWB). The origin of UWB technology dates back to the early 1960s when research experimented with the time-domain of electromagnetic-wave propagation. In a seminal paper Ross and Benet summarized UWB's early applications [4]. Ross was the first researcher to demonstrate an UWB communication system in 1986. Until 1994, the majority of the work was performed under US government programs. With rulings of the Federal Communications Commission (FCC), after 1994, there has been an increase in non-governmental related research and an increase in the number of UWB government agencies and companies that are greatly accelerating the development of UWB technology [5]. Since then, UWB technology has shown to possess unique advantages for precision localization applications. The use of short pulse radio frequency (RF) waveforms provides inherent precision for time difference of arrival measurements, as well immunity to multipath effects in indoor applications.

To measure larger distance and the locations of objects more efficiently and potentially identifying them at the same time, requires tagging the construction resources. UWB sensing has a particular advantage compared to RFID sensing, since it gives accurate 3D location values in real-time. Since GPS requires satellite or base station connection it is mostly limited to outdoor applications. UWB's main limitation at this point is a necessary measurement infrastructure, but once set in place can stay for at least the project duration. Material tracking or supply chain, however, does not stop once the shell structure of the building is erected. Many subcontractors come on site once the interior finishing of a building starts and even after the building is finished (e.g., maintenance). For example high-rise projects, often store materials and supplies in already built but unfinished building floors. If real-time tracking construction resources and progress should become a new tool in construction and project management, decision making at all levels (workforce, field manager, project manager) will require technology to record location and movement of construction resources at different time intervals, in three-dimensional space, at all times, safely, and at low cost and maintenance.

3. RESEARCH OBJECTIVE

The research objective is to assist the construction industry in determining the location and trajectories of resources (workforce, material, equipment). The purpose of this research is to demonstrate the applicability of Ultra Wide Band for construction and in particular to measure accuracies in field applications such as work zone safety, material and work task productivity tracking.

4. REQUIREMENTS FOR THE UWB SYSTEM

From an implementation perspective, the main points of the UWB system requirement can be summarized as follows:

- Accuracy: UWB must be better than existing solutions including GPS. An error in any dimension of less than 1m at update rates of at least 1Hz is acceptable for many construction applications, e.g., material tracking.
- Size and Cost: Depending on the application, the system needs to be affordable, small, and preferably offer full wireless operation, e.g. range between US$0.1-10 and a few grams per tag.
- Ease of use and cost: Fixed installation of hardware and antennas should require less setup and maintenance. Running cost should be minimal.
- Legality: Standards and regulations in each country differ and need to be developed and followed.
- Interoperability: Communication to other technologies must be likely, e.g. handhelds, but should not interfere and needs to co-habit with other signals in the radio frequent (RF) spectrum, e.g. inside and outside buildings.
- Range: To be practical in construction, signals must be useable over 150m between fixed and potentially mobile receivers, and need to work in object cluttered environments, e.g. walls, steel.
- Multipath: It must work well when there are multipath components at all delays from a few centimeters to several meters, similar in level to the straight path (and up to 10 dB higher in a few cases) [6].

5. EXPERIMENTAL SETUP

The experiments conducted inside the laboratory and on the construction job site used the following configuration of an Ultra Wide Band system (see principle layout illustrated in Figure 1):

- Central hub processor and computer interface
- Receivers (6 Mid Gain and 3 High Gain)
- CAT-5e shielded cables (several lengths)
- Tags (up to 30, including one reference tag)

The receivers/antennas are connected via shielded CAT5e cables to the hub. Each cable powers the connected receiver(s) as well as transmits the tag identification and time readings back to the hub. A reference tag in line-of-sight of the receivers or of receiver subgroups is placed preferably in the center of the space observed. The location of each tag is calculated based on synchronizing the arrival signal after the time-of-flight principle. Signals between receiver and tag can then generate real-time two-dimensional positioning data if at least three receivers are used. Real-time 3D location sensing requires at least four receivers, preferably at locations with significant difference in elevation.

The UWB tags come in form of a small badge (6.5x3.4x0.6cm), asset cube (2.9x2.9x2.5cm) or micro rectangular (1.3x2.5x0.6cm) form. The weight for each tag is less than 12grams. The update rate of the radio frequent (RF) signal of each tag is fixed and can be up to 60Hz, otherwise comes at 30Hz, 15Hz, 5Hz, 1Hz, or even lower frequencies. The range of the tags, depending on the receivers used, can be up to 200m (High Gain directional receiver).

Before measurements in the field or in the laboratory were conducted a Total Station recorded the 3D location of all receivers. This positioning data needs to be implemented in the hub's processing unit. Two initial experiments are presented to demonstrate the potential of the technology as well as preliminary results:

(1) Indoor tracking of humans within the laboratory. Evaluate UWB system under near optimal conditions to measure accuracy and precision.

(2) Job site tracking of workforce and steel erection. Evaluate the UWB system under realistic conditions with ambient influences, e.g. sunlight, metal interferences, at large scale of 60x60m.

6. EXPERIMENTS AND RESULTS

The condition and results of one indoor and one outdoor experiment are discussed in the following paragraphs.

A data processing and graphical user interface (GUI) exists that analyzes the RF signals inside the

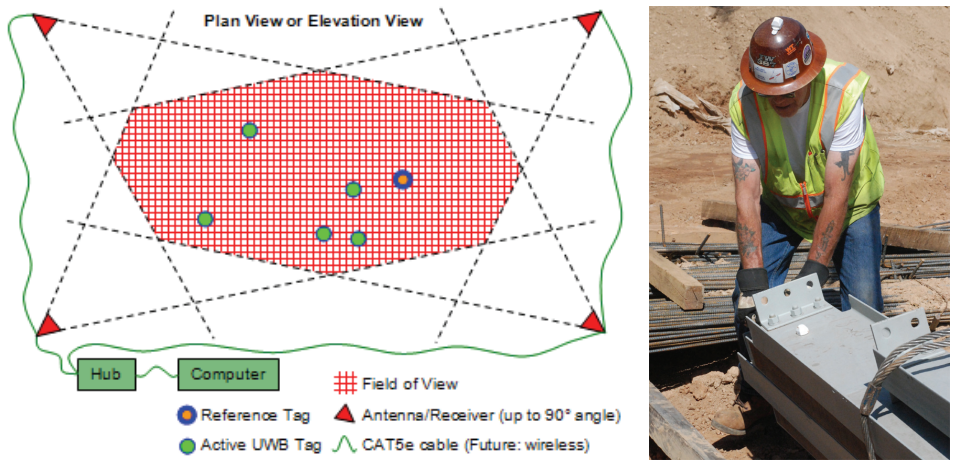


Figure 1 Ultra-Wideband Receiver and Hub Configuration, UWB Tags on Ironworker and Material

hub and displays the location of receivers and UWB tags in real-time. An example snapshot of the GUI with nine receivers and a few tags is illustrated in Figure 2. Preliminary data processing algorithms and visualization tools were developed to display the position data in a MATLAB environment.

The indoor experiment used four Mid Gain receivers and two asset tags at different update rates. The arrangement in rectangular form of 6x3 meters allowed placing the reference tag in the middle. Since only 2D data was collected, the (X, Y) position of single tags is displayed in Figure 3. The trajectories of two tags (two walking humans) are shown in form of a "Snake" (upper right image) as well as the overall trajectory in plan view (bottom right). The position accuracy was significantly better than 1m.

In a next step, the initial work on algorithm development included an obstacle avoidance algorithm that sends off an alarm whenever the tag (human) is in a predefined hazardous zone or when tags get too close to each other. User-defined values can be set, e.g. for the minimum allowable distance the tags can have to each other, or the location and size of the hazardous work zones. Once the criteria are not met an alarm window goes off (lower left in Figure 3). This has significant value for safe (and automated) machine operation when machine operators have limited visibility or workforce is unaware of dangerous situations. Overall awareness and safety can be increased by issuing alarm signals to workforce, operators, field safety personnel, management in form of acoustic, visual, vibration, or text messages. This basic proximity algorithm experienced a 100% detection rate, in real-time (in 3D), and at the same frequency as the tag with the highest update rate (60Hz).

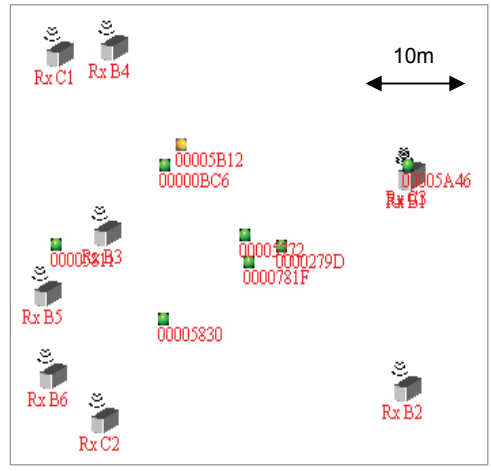


Figure 2 Receiver and Tag Layout in Field Trial

In a second experiment, the UWB system was used to track the material flow during the steel erection process of a three story research building. Upon truck arrival, the UWB tags were placed on the individual steel beams on the truck bed. The beams then were either moved temporarily to a laydown yard or hoisted directly into their final location

using a mobile crane. Three-dimensional positioning data to each UWB tag was recorded and start and end point compared to a ground truth measurement using a Total Station. Tags were also placed on a few workers, materials, crane location, and crane hook. The layout of receivers and reference tag in the outdoor experiment is illustrated in Figure 2 (plan view). Three receivers were installed on already built structure at elevated level.

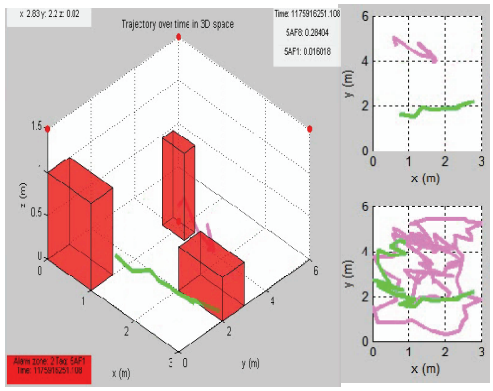


Figure 3 Active Work Zone Safety includes Predefined Hazardous Zones, Travel Paths, and Alarm Box



Figure 4 Sensor Field Setup, UWB Tag on Hook

An in depth experimental analysis is underway. Preliminary results can be determined as: (a) Installation time (1 day) was extensive for the short amount of time of the entire experiment (2 days), but once receivers, cables, and reference tag were installed the UWB system was easy to maintain and delivered positioning data that reflected the movements on site, e.g. tag on hook (Figure 4); (b) Although the UWB equipment is commercially available, it is predominantly used in manufacturing, distribution centers, or prototype evaluation projects; Field trial measurements in the rough construction environment were successful and the design of the equipment is robust enough to be placed on steel beams and withstand smaller punctual hits. (d) One tag had error readings due to a lose tag antenna and was removed from the experiment.

7. OUTLOOK

Ultra Wide Band positioning may offer many solutions to existing problems in construction and elsewhere. The Real-time Automated Project Information Decision Systems (RAPIDS) Laboratory in the School of Civil and Environmental Engineering at the Georgia Institute of Technology currently focuses on the following research and application areas in UWB [7]:

- Develop data collection and processing algorithms as well as user interfaces for accurate and precise positioning data in real-time.
- Determine the impact of UWB for the construction industry, e.g. accuracy, feasibility, and future UWB needs. Development of solutions to the following application areas that can expand the use of UWB.
- Improve simulation in construction by providing real-time and accurate positioning and time data, e.g. crane, truck-excavator.
- Increase motorist's and workforce awareness in transportation and construction work zones, i.e., during night road maintenance work using active real-time safety.
- Enlarge awareness of emergency responders in navigating through buildings, i.e., Georgia Emergency Responder test bed.
- Enhance existing supply chain and workflow productivity strategies and practices by locating and tracking resources (workforce, materials, equipment) on construction sites in real-time.
- Optimize sensor layout (and improve hardware for wireless and low power consumption).

8. CONCLUSION

This paper has demonstrated that a standalone or joint approach of using existing and emerging technologies such as Global Positioning System

(GPS), Radio Frequency Identification (RFID), laser tracking, and Ultra Wide Band (UWB) comes each with a variety of benefits and limitations. Tracking and monitoring construction resources (workforce, materials, and equipment) and activities in real-time, accurately, in indoor and outdoor situations is made possible using Ultra Wide Band technology. Preliminary research efforts conducted in the Real-time Automated Project Information Decision Systems (RAPIDS) Laboratory at the Georgia Institute of Technology show some benefits this emerging technology can offer to the construction industry. The results of this paper conclude that in particular the existing needs for real-time working applications such as work zone safety, job site monitoring, and resource tracking may offer a high return on the investment in UWB. Further research is needed to explore UWB's full potential for construction and other application areas. Investigations are pending and are currently under research in the RAPIDS Laboratory.

9. ACKNOWLEDGMENT

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DEVELOPMENT OF WIRELESS MODULE FOR TUNNEL VIBRATING WIRE TYPE SENSOR

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ABSTRACT

Tunnel construction is being increased rapidly in Korea. About 60 percent of total tunnels have been constructed for the last 10 years. So systematic tunnel measurement and maintenance system have been needed. Vibrating wire type sensor is widely used in tunnel measurement system because of their stability and durability. Vibrating wire element is applied strain gauge, earth pressure cell, temperature gauge, piezometer and so forth. But conventional vibrating wire sensor is using wire-based communication and many problems have been occurred like high cost and disconnection. So we developed low-cost and effective wireless communication module for vibrating wire type sensor using pulse counting and Zigbee technologies. This module can change conventional wire-based data log and communication into wireless one instantly. This paper describes prototype of wireless communication based vibrating sensor system and results of field test.

KEYWORDS

Tunnel, Measurement, Zigbee, Wireless

1. INTRODUCTION

It has been steadily increasing tunnel construction since more than 70% of the nation consists of mountain region in Korea. The number of tunnels in national road has been growing for ten years[1]. And it was significantly increasing in highway. Therefore it is very important for monitoring to better accomplish tunnel construction and maintenance, and a systematic monitoring plan should be carried out for acquisitioning useful and reliable field measurement information. However, the tunnel monitoring has been conducting in limited area and has not organized in acquisition data from sensors. So the measurement data from sensors has not used in construction and maintenance in real situation of tunnels. The reasons are that existing wired sensors are complicated for

control and maintenance. Moreover expensive data logger has less economical feasibility. As a result it is import to development of sensors having economical feasibility, to effective sensing and control of sensors in tunnel maintenance. In this paper, Zigbee based wireless communication prototype module which could change current wired vibration wire sensor into wireless sensing device was introduced. Field tests and the results using developed wireless sensor module are also included.

2. TUNNEL MEASUREMENT AND VIBRATING WIRE SENSOR

Tunnel measurement for construction can be divided into 'daily management measurement(A type) and 'representative point measurement(B type)'. The daily management measurement is subject to all the construction site, which is to confirm the safety of the tunnel construction and include face mapping, lining displacement measurement, tunnel arch subsidence measurement, soil subsidence measurement. The representative point measurement is subject to a inspection of design, planning of construction and changing design and include underground displacement measurement, rock-bolt axial force measurement, shotcrete stress measurement, underground subsidence measurement [2][3].

Vibrating wire sensor is widely used in these measurements mentioned above. But they have problems of cost, usability and durability because they are wire based. Therefore, most engineers in tunnel construction site perform minimum level of measurement at necessary point.

3. WIRELESS PROTOTYPE OF THE VIBRATING WIRE SESOR

3.1 Concept

The wireless module for a vibrating wire sensor made in this study is connected to various types of vibrating wire sensor installed in the tunnel as shown in Fig. 1 in order to relay or transmit sensing data in a wireless method.

All the data in sensors to which the module is connected are ultimately transmitted to the notebook computer on the spot. Here, the notebook computer using Zigbee gateway and USB is used as the operating server for manufacturing the prototype in this study. CDMA communication module and LAN can be applied to the notebook computer in the event that measurement in a long distance is needed.

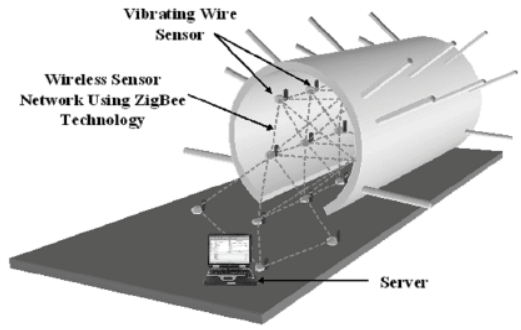


Figure 1 Concept of Wireless Tunnel Measurement

3.2 Wireless Module

The wireless sensor module consists of a vibrating wire A/D circuit, a Zigbee communication circuit, a battery, packaging, operation software, and a notebook computer as shown in Figure 2.

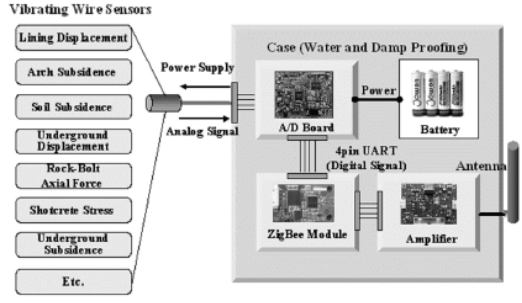


Figure 2 Composition of Wireless Module

Of the components, the vibrating wire A/D circuit is a circuit to convert analog signals into digital pulse. The vibrating wire A/D circuit, which has an interface (4 pin) to be connected to sensors, provides sensors with electric power, changes the cycle and frequency of measurement, and conditions (filters or amplifies) analog signals as well as plays the basic function, A/D converting. The vibrating wire A/D circuit was manufactured by miniaturizing a conventional vibrating wire

multi-channel data logger, so that it plays the same functions as a conventional logger.

Table 1 Specification of A/D Circuit

Item	Specification
Sensor	vibrating wire sensor
Sensor Interface	4pin
Zigbee Interface	4pin (UART)
Frequency	450~6,000Hz
Resolution	0.1Hz
Accuracy	0.01% FSR
Temperature	-40~60℃
Memory	6,000 Read/Record
Power	6V (4 CR123A Battery)

Sensing data converted into digital pulse are transmitted to the Zigbee gateway through the Zigbee communication circuit using a RF (radio frequency) wireless method. The data received are saved in the notebook computer that works as a server on the spot, and displayed as graphs by the operation software. Detailed specification and prototype are as follows.

Figure 3 shows the prototype of wireless module for vibrating wire sensor. The module has two channels to connect sensors.

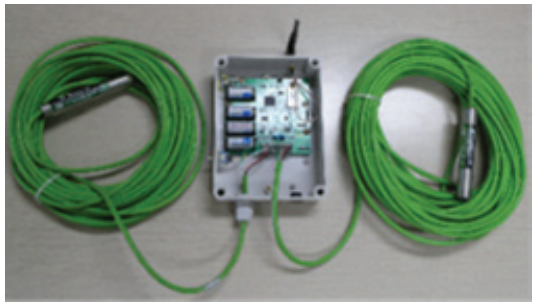


Figure 3 Wireless Module & Vibrating Wire Sensor

3.3 Operation Software

A notebook PC is used as a data server and connected to the Zigbee gateway using a USB port. The operation software is composed of application programs based on Microsoft Windows Operation System, and has the functions to automatically save and sort the data received from the Zigbee gateway in database(Figure 4). In addition, the data can be exported as a file format like a spreadsheet using MS Excel. Moreover, the operation software can display sensing data in graph format in a real time and adjust the sensing cycle between 1 and 86,400 seconds. The operation software has the function to check overall network status and uses the Mesh Networking, so that the data transmitting path can be automatically changed in the event of disconnection of a sensor (ad-hoc).

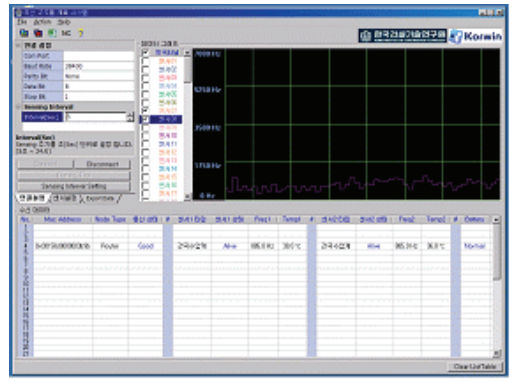


Figure 4 Operation Software

4. FIELD TEST

The filed test for the wireless module for vibrating wire sensor and operation software developed was performed in the Bukbyeon tunnel located in Gimpo-si(South Korea). This tunnel is being currently used, so that noise and dust are generated due to continuous vehicle access. The experiment was conducted in order to measure the maximum communication distance and verify smooth operation of the Mesh Network. At the outset, communication disorders were expected due to diffused reflection caused by vehicles, generation of interfering waves and wave absorption by the tunnel walls and the road surface. Unlike the expectation, the maximum communication distance

is more than 200m and the Mash Network works without difficulty. It is believed that the inside of the tunnel is made of nonconductor that plays a type of waveguide.



Figure 5 Field Test in Tunnel

5. MEANINGS AND FUTURE IMPROVEMENT

5.1 Distributed Data Logging in Tunnel

A conventional tunnel measurement system has the central data logger and adopts the wired transmission method. This method is impossible to receive data from dozens of sensors connected to the logger in the event of disorders of the logger or the communication line. However, when the data logging is distributedly performed in each node and the communication is conducted using a Zigbee Mesh Network, there is almost no influence on the overall system in the event that several nodes do not work. Durability of communication will be possessed like the Internet. In addition, the conventional logger needs to be composed of a high-performance CPU, a memory, and a circuit to perform logging from dozens of sensors, and its cost is, therefore, expensive. However, when the distributed data logging is performed, the module can be manufactured at a low price.

5.2 Future Improvement of Communication Algorithm

The wireless networking for the system currently developed is done for 24 hours to maintain the Mesh Network. It consumes a lot of electricity, and it can actually perform measurement only for at least 2 days up to maximum 5 days. This method can be used to perform a provisional measurement with a view to assessing safety of a tunnel currently used. Therefore, the algorithm should be revised for a maintenance measurement in a long term perspective.

The maintenance measurement in a tunnel is classified as the static measurement, and it is enough to carry out the measurement once a day. Therefore, each module waits in a sleep mode almost 24 hours and wakes up at a set time everyday to conduct measurement and communication for a certain period of time (5 minutes). For this method, time synchronization is important and the standard time is transmitted from the gateway connected to the server when all the modules wake up from the sleep mode, so that the time can be identically kept. If the method is used, the hardware with the battery currently used can arithmetically perform the measurement for at least 288 days up to maximum 1,440 days.

5.3 Future Improvement of Data Management System

When the system is expanded and used in many tunnels (or nationwide), it is expected that a large volume of data should be verified, integrated, and managed in a real time in the future. To manage such a large volume of sensing data, a lot of middleware has been recently developed all over the world. ETRI (Electronics and Telecommunications Research Institute) in Korea developed middleware called Ubicore[4]. The middleware was developed to create or delete space for data to be saved, and perform sampling of sensing data, data analysis and inquiry by using XML-based user designating context..

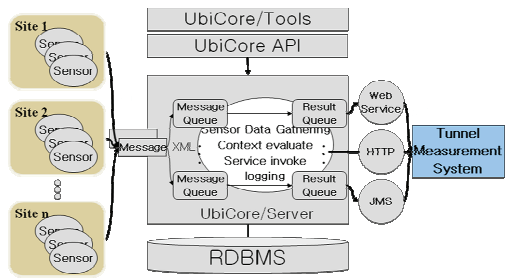


Figure 6 Concept of Data Management System

The Ubicore will be used in relation with 'systematic management of the measured data and database system development' for this study, and Fig. 6 shows a system designed to process data from a lot of tunnels. Using the designated XML context, a lot of tunnels shown on the left of the Figure transmit sensing data, and Ubicore analyzes, arranges and saves the context in database. When a user requests data via query, Ubicore interprets query and fetch the data from the database using the web-service, HTTP, or JMS (Java Message Service).

5. CONCLUSION

There are many barriers for using sensors in tunnel such as noise, vibration, dust, humidity. The developed wireless communication module has significant meaning in using current vibration wire sensor by integrating with wireless communication function. Therefore, using this module, existing vibration wire type sensor can be easily embeded wireless communication function. Moreover, this module can be applied widely and improve applicability of sensors in tunnels and other social infrastructure system. In addition, field tests conducted by using this prototype module to verify its performance. The limitations found in field tests in current module including battery usage and sensing zone generation will be complimented.

6. ACKNOWLEDGMENT

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AUTOMATION AND WIRELESS COMMUNICATION TECHNOLOGIES IN ROAD REHABILITATION

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ABSTRACT

The goal of the project is to survey the applicability of machine automation and wireless communication technologies in road repairing and surfacing. The focus is on the control of the worksite and road repairing and road surfacing process. This process contains design, construction, quality control and work site management. The objective is to study, how different machines, e.g. asphalt mixing plant, trucks, paver and vibrating roller, can be equipped with wireless data connections and automation systems and what are the possibilities and benefits of ICT and machine automation in this application field. During year 2006 visits to the asphalt pavement repairing sites have been arranged. Different asphalt repairing methods as well as practices in production and transportation of asphalt mass have been studied. Persons that are working in asphalt work have been interviewed. Asphalt transportation and it's synchronisation to the asphalt spreading and asphalt production is one detected area of development. A concept of an asphalt process management system has been developed. The concept consists of connecting the trucks, asphalt pavers and the asphalt plant to a database by using wireless data communication. Process variables, such as mass temperature and transportation time, are measured in real time and saved to the database. From the information collected to a database an up-to-date view that shows the functioning of the whole process can been generated. With the better control of asphalt transportation the defects in pavement quality can be reduced. The goal is to test this concept by developing a prototype system and by arranging small scale field tests during year 2007.

KEYWORDS

Road Construction, Pavement, Automation, Wireless Communication

1. INTRODUCTION

In this research the focus was on repairing pavement failures on old roads and pavement laying on new roads. Much research work has been done automating different machines in road building and road rehabilitation [1]. In this research the focus was how a group of machines and a process they constitute can be managed better by applying ICT, embedded sensors and wireless communication technologies.

Pavement laying process consists of production of the asphalt mass, transportation of the mass to the work site, asphalt laying and compacting. When repairing old pavement, the old pavement material is usually recycled. This can be done using in-situ methods, e.g. using asphalt remixer. Other method

is to use asphalt cutter to remove old surface and transport the crushed pavement to the asphalt mixing plant for recycling.

During this project many professionals working in asphalt production and spreading were interviewed. The co-ordination and synchronization of the asphalt production in the asphalt mixing plant, asphalt transportation and asphalt spreading in the work site was seen challenging. Many variables, e.g. weather, traffic conditions, failures of the machines, the number of trucks available and transportation distance, have an affect to the process.

In Finland mobile asphalt mixing plants are widely in use. Distance to the gravel storage place and environmental restrictions have to be taken into account when selecting the location of the asphalt mixing plant. On mobile asphalt mixing plants there are usually no silos for asphalt mass. So every asphalt batch is made directly to the loading pallet of the truck. The placement of the mobile asphalt mixing plant has to be chosen so that the transportation distance to the worksite doesn't exceed 100 km. This ensures that that the asphalt mass doesn't cool too much during transportation.

Usually the asphalt mixing plant produces asphalt mass for more than one paver. It is important for asphalt mixing plant operator to know how each paver is progressing in order to adapt the production and transportation of the asphalt mass to the need of mass on each paver. In order to accomplish good pavement quality, asphalt spreading should be done without unnecessary stops. The transportation should work so that the paver doesn't have to wait for mass. On the other hand it is important that the truck doesn't have to wait for unloading so long time that the mass cools too much.

Also part of logistics of the asphalt production and pavement laying is transportation of the materials (bitumen, filler) and heavy fuel oil. Usually in the mobile asphalt mixing plant there are no containers for large amount of bitumen and oil, so bitumen and oil are transported to the mixing plant usually for the need of one workday. For this reason it is important to track the progress of the pavement laying and estimate the need of bitumen and oil for the next workday.

The conclusion was that with the better synchronization of asphalt production, transportation chain and asphalt spreading the performance of the whole process can be improved and a better pavement quality achieved. More up-to-date information about how the process work is needed. This information should be shown illustrative form. In this paper a concept how asphalt process can be instrumented is described. Currently the development of the prototype is underway the first small scale tests will be done during year 2007.

2. CONCEPT OF AN ASPHALT PAVEMENT PROCESS MONITORING

2.1 Background

In order to achieve good pavement quality the asphalt production, transportation, spreading and compacting must be working seamlessly. The hypothesis was that the process is similar to a normal plant with the difference that some of the production machines are outside of the fences of the plant. Nevertheless these machines can be connected to the plant by applying wireless communication. So trucks and asphalt pavers can be equipped with embedded measurement devices that measure process variables and these machines are connected to the asphalt mixing plant. This enables automatic data collection. Applying web technologies the collected data can be stored and formed to usable form for different users. Users have access to the data by using their personal mobile devices or computers.

VTT has previously tested mobile technology in "Wireless construction site" – project [2], where a system for managing mass transportation tasks in road construction was developed and tested. Truck drivers used their mobile phones to access and store data about transportation tasks to the database. System was based on Java applications in phones and GPRS (General Packet Radio Service) as communication technology. In this project the experiences of mobile technology were promising. One of the main advances was that data collecting can be done using very cheap and portable device. No constant installations to the trucks were needed. This makes easy for sub-contractors to take the system into the use.

One of the disadvantages discovered is that the system is totally dependent of the users. This makes the system prone to human errors and it depends much on motivation and carefulness of the user, how reliable and up-to-date the collected data is. Another problem with mobile phones is that they don't provide interfaces for adding sensors and measuring process variables.

At the same time embedded system and wireless communication technologies have developed so that even more simple embedded devices can be connected to the internet e.g. using GSM/GPRS modules and GPS positioning can be added to the embedded system. This enables cost efficient instrumentation of the mobile machines.

As a goal of the development work was to make the data collection and measurements of the process variables as automatic as possible and minimize the interaction needed from the users. Embedded measurement modules are used for data collection. VTT have already developed a measurement module for measuring vibrations from the work machines [3]. This module was used as a basis for developing a prototype system.

Compared to the mobile phone technology a disadvantage is that permanent installations to the machines are needed. Mobile phone technology and embedded measurement are not mutually exclusive. Mobile phone applications can be used for data collecting tasks that need user interaction and distributing information to the workers.

2.2 Users

Workers in the worksite need information that is relevant to their work task. The goal is to provide needed information in a visual form. The users in this case are:

- work supervisor
- asphalt mixing plant operator
- asphalt paver operators
- truck drivers

Work supervisor and asphalt mixing plant operator need information concerning the whole process, e.g. operating status of all the pavers as well as locations of the asphalt trucks. This enables for example allocation of the trucks between different pavers as well as tracking the progress of the paving. Operator of the asphalt paver needs information related to his own paver. Important information for him/her is for example when asphalt trucks are arriving to the paver. For truck drivers important information is the route to the paver as well as data needed for billing, e.g. total amount of transported mass, driving distances, waiting time etc. Example of a process view is shown in figure 1.

2.3 Data collection and visualisation

2.3.1 Performance of the transportation chain

The performance of the transportation chain can be evaluated by measuring how much time is spend in each part of the cycle of asphalt truck:

- Loading time [min]
- Transportation time [min]
- Waiting time for unloading [min]
- Unloading time [min]
- Returning time [min]
- Waiting time for loading [min]

Other measured variables are:

- Transportation distance [km]
- Amount of transported asphalt mass [t]

From these measurements the instantaneous performance [t/h] can be calculated. This can be compared to the theoretical performance achievable in the current traffic conditions. This can be estimated assuming the waiting times to be zero and trucks are transporting maximum loads. The key values that represent the performance of the transportation chain can be updated in real time, figure 1.

2.3.2 Tracking of truck locations

Tracking of the asphalt track locations is used for estimating the time when a truck arrives to the paver or returns to the asphalt mixing plant. Asphalt paver operator can decrease the speed of the paver to avoid stopping if he/she has the information that the next truck is delayed. Also asphalt production at the asphalt mixing plant can adapted to the number of returning trucks. If there are no trucks coming for a while, the asphalt plant can be shut down in order to save fuel. In some cases it is useful to wait several trucks to return and then restart the plant. This way unnecessary restarts can be avoided.

Traffic conditions affect to the transportation time. Using GPS and time measurements the arriving time of the truck can be estimated if the transportation times of the previous trucks on the same route are known. Truck locations and estimated arriving times can be illustrated to the operators, figure 1.

2.3.3 Measurement of the temperature of the asphalt mass

The mass temperature should not be lower than 150 ºC in order to accomplish good pavement quality. So system for monitoring cooling of the mass during transportation was seen important. This can be achieved by installing IR sensors to the trucks and pavers.

2.3.4 Monitoring of the progress of the asphalt paving

In order to monitoring the progress of the asphalt paving the paved distance and speed of the paver need to be measured. If a spreading width is also measured, paved area can be measured. If this information is available in the asphalt mixing plant, production and transportation can be adapted to the need of asphalt mass on different pavers.

2.3.5 Registration of the truck loads

During the paving the operator of the paver calculates the needed amount of asphalt mass and sends this information to the asphalt plant. The operator of the paver keeps track of transported amount of mass. Asphalt production on the asphalt plant is highly automated and information about each batch of mass is stored to the system of the plant. When GPS positioning is used in trucks, also information related to the transportation (e.g. unloading location, time, transportation time, temperature, truck ID) can be collected and stored. This information is useful for example when tracking reasons for quality defects or reporting done work to the customer.

2.4 Communications

Both long range communication and short range communication technologies are utilized in the system. Long range communication is needed for data transfer between embedded measuring devices and a server and for providing access to the server for users. GSM/GPRS services provided by telecommunication operators are used, figure 2.

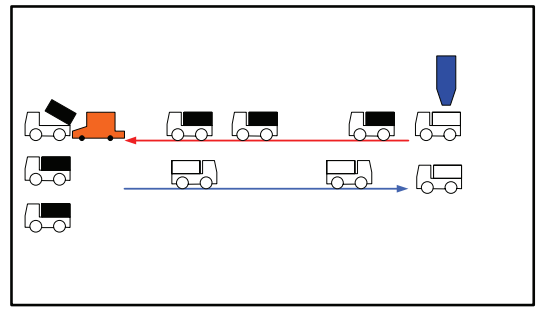


Figure 1 An Example of a Process View

Short range communication is needed for establishing a direct data transfer link between two machines. In this case a truck can connect directly to the asphalt mixing plant during loading and to the paver during unloading. This makes possible to transfer the information related to the asphalt load (load ID, amount of mass) from the asphalt mixing plant to the paver with the truck. Short range communication link can offer a backup system if GPRS service is unavailable, Figure 2.

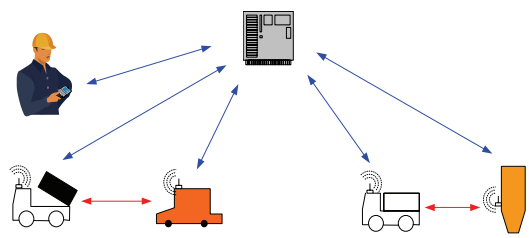


Figure 2 Short and Long Range Communication Technologies in Pavement Process Control

It is considered that for all special cases it not necessary to develop a mobile application. For example a truck driver can use a shortwave radio to inform the asphalt plant operator about delay or a technical problem. Asphalt plant operator then inputs this information to the system. After that the information is available to all who need it.

3. PROTOTYPE SYSTEM

3.1 Prototype System Overview

Currently the development of a prototype system based on concept described above is on a way. Parts of the prototype are:

- Embedded measurement modules
- www server
- Web-based user interfaces for workers

Communication between measurement modules and server is done using a standard XMPP protocol [4]. XMPP protocol is very lightweight and this makes it useful when connecting embedded devices to the internet [5]. On the server there is a XMPP server to which the XMPP clients are connected. PHP Agent is used for accessing the mySQL database. PHP is also used for generating dynamical web pages. Most of the data processing is done on the server. GPRS is used for wireless data transfer between measurement modules and the server, figure 3.

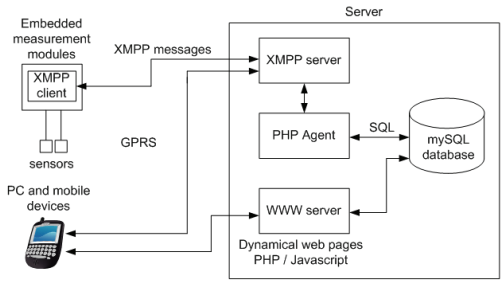


Figure 3 Prototype system overview

3.1 Embedded Measurement Modules

In figure 4 an embedded measurement module is shown. In the Module Atmel FPSLIC microcontroller is used. In this application an IR sensor (1) for measuring mass temperature, an inductive proximity sensor (2) for detecting unloading and a GPS positioning module (4) are connected to the module. Also some switches for the operator will be installed.

For communication both GPRS and nanoNET TRX radio modules (3) are installed inside the box. NanoNET TRX radio module from Nanotron Technologies GmbH is used for establishing a direct communication link between two machines. NanoNET technology is suitable for harsh environments and VTT has used it in different industrial applications [6]. Technical challenge is to open the connection automatically without user intervention within a few seconds.

The task of the measurement module is to detect different events according to the programmed rules and if an event occurs send XMPP message to the server. Events can be detected by using:

- real time clock
- GPS position
- sensor data
- connection to the other machine
- request from server

For example if the arrival to the asphalt plant is detected according GPS position, a message to the server is send. Events are kept simple. Module ID, event ID, GPS position and time are always send and sensor values etc. are added to the message if needed. Server handles the event according to the event ID.

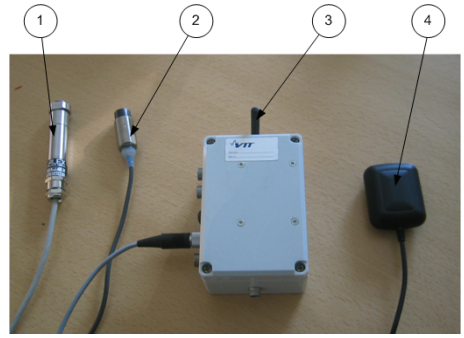


Figure 4 Embedded measurement module

4. CONCLUSIONS

In this paper a concept how ICT, embedded sensors and wireless communication technologies can be utilized in managing pavement laying process. Asphalt mixing plant, asphalt trucks and pavers are connected to each other using wireless technology. Embedded sensor modules are used for automatic data collection. Data is formed to a visual form so that overall performance of the process can be monitored. Decision making is still done by human operators, but the system provides them up-to-date information.

There is always a risk that automatic data collection causes agony and is not accepted by the users. On the other hand if the system provides useful information in an easy form, it can reduce the workload and the stress of the operators. At present much data from the process is collected using handwritten forms. Processing handwritten forms can be laborious and slow. Automatic data collection can also reduce this work significantly.

Technical challenge is to achieve sufficient reliability. Also cheaper, smaller and easier to install measurement modules should be developed. Measurement modules should provided interfaces for various sensors and capability to use sensors that are already attached to the machine, e.g. through CAN bus interface. XMPP messaging is based on XML technology. Binary XML [7] is also a potential technology to enhance XMPP messaging, because it provides efficient data compression for XML data. The goal is to build a first prototype system and to test it during year 2007 and based on the experiences improve the system.

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OPEN-BUILDING MAINTENANCE MANAGEMENT USING RFID TECHNOLOGY

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ABSTRACT

By applying the Radio Frequency Identification (RFID) technology, this study embedded the RFID tags in the components of open-buildings to store the raw design data so that data can be passed to the maintenance phase and automatically provided to the building users. For this purpose, this paper focused on the application of RFID for developing an Open-Building Maintenance Information System (OBMIS) for OB maintenance management. Three functional modules were developed in the OBMIS, namely (1) the support components information management (2) the infilled components information management and (3) the reanalysis/redesign module. In the support and infilled information management models, users can write and read the components' information, such as material type and construction information etc., within the RFID tags by using Personal Digital Assistant (PDA) for maintain management. Meanwhile, in the reanalysis/redesign module, for building extension or reconstruction, users can acquire and transfer the structure parameters from the components' tags to external analysis systems, such as SAP2000 etc., for structure safety analysis. Summarily, by using the OBMIS, not only the data in the design phase can be transferred to the maintenance phase, but also the data can be provided by the building itself so that the efficiency of OB maintenance management could be enhanced.

KEYWORDS

Open-Building, Support System, Infill System, Radio Frequency Identification, Maintenance Management

1. INTRODUCTION

In Recent years, the number of large scale construction projects is decreasing in Taiwan. The demands of modifications and maintenance for legacy buildings arise day by day. The hazardous waste and the resource consuming resulted from demolishing and re-construction in maintenance phase were increased. Therefore, the idea of reusable building components was proposed to reduce the unnecessary environmental pollution and resource waste. The Open-Building (OB) architecture philosophy was one of the well-known solutions addressed for this sustainable building idea [1].

OB architecture philosophy was proposed in 1960s which advocates the usage of reusable and changeable building elements for enhancing the flexibility of buildings and decreasing the resource

consuming situations in the maintenance phase. Generally, an OB building is composed of two systems; namely, (1) the support system and (2) the infill system. Two systems are composed of usable and changeable structure components and fitting components respectively. Therefore, ideally, not only the structure and interior layout of an open building could be remodeled, but also the building could be relocated based on the user's dynamic necessary in the maintenance phase. That is, owners can change the purpose of an open building by remodeling the support and the infill systems. In Taiwan, as purpose conversions occur for a building in the maintenance phase, the relevant design data and a new structure safety analysis report need to be submitted to the superintendent of the Taiwan government. However, since raw design data is usually missed due to improper preservation through the whole life cycle of a building, the raw design data and the structure model may need to be recollected and rebuild. This circumstance decreases the efficiency and advantage of open buildings. To overcome this problem, to store the raw design data within the building itself to provide design data immediately and correctly may be an idea to enhance the maintenance efficiency of open buildings.

Meanwhile, the Radio Frequency Identification (RFID) technology is a wildly-used IT application in these years due to its wireless identification data providing ability [2]-[4]. Many studies have applied RFID for issues of material management, pipe tracking in the construction industry [5]-[7]. The self-data-providing ability against environmental erosions increases RFID's the application potential in construction industry comparing with the barcode technology [8]. Accordingly, RFID might be a proper application technology applied to the maintenance phase in the build life cycle. Based on this concept, this study aims at embedded RFID tags into open building's elements, such as support and infilled system components, so that open buildings can automatically provide the essential design data for remodeling to enhance the maintenance efficiency of open buildings. For this purpose, a RFID-based open-building maintenance (RFID-OBM) model and an Open-Building Maintenance Information System (OBMIS) were proposed in this study. In the RFID-OBM model, the remodeling behaviors relevant to open buildings' purpose conversions was firstly identified, so that the essential information and information flows corresponding to the remodeling behaviors can be determined subsequently. Based on the RFID-OBM model, the OBMIS was developed to be the platform for managing the components' information, and assisting owners with remodeling works. By using the developed OBMIS, users can utilize portable devices, such as personal data assistant (PDA) and laptops, to acquire the components' raw design data from the open building itself, and the acquired data can then be passed to the external structure analysis softwares, such as SAP2000, ETABS etc., to analyze the safety for use conversion of the building. In the following sections, the RFID-OBM model and the development of the OBMIS are discussed.

2. RFID-BASED OPEN-BUILDING MAINTENANCE (RFID-OBM) MODEL

RFID-OBM model is the basis for developing the OBMIS. Three parts were determined in the RFID-OBM model, namely (1) open building remodeling behaviors, (2) essential information for open building remodeling behaviors and (3) RFID-based information management mechanism for open building maintenance. The open building remodeling behaviors are identified to be the first part of the model which not only presents the functional requirements of the OBMIS, but also is the foundation for determining the essential information of remodeling works. Based on the determined remodeling behaviors and essential information, the RFID-based information management mechanism was proposed.

2.1 Open Building Remodeling Behaviors

To identify the remodeling behaviors of open buildings, this study analyzed the causes of conversions to classify conversion types and conversion behaviors and to create the relations between conversion and remodeling behaviors as Figure 1 shows. In Figure 1, seven conversion behaviors were determined. Each conversion behavior has its related component type/s, and each component type has a set of remodeling behaviors; i.e., as one conversion behavior occurs, the components related with it need to be

remodeled based on the requirement arisen from the conversion. Three remodeling behaviors were determined in this study, namely (1) redesign (2) reanalysis and (3) reconstruction. Only support system remodeling needs to reanalyze the structure safety due to Taiwan regulations.

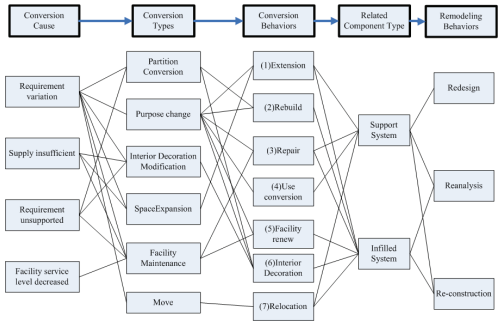


Figure 1 Remodeling Behaviors vs. Conversion Behaviors

Accordingly, once a conversion arises, the necessary information related to the remodeling behaviors needs to provide to the designer. For this purpose, the essential information for remodeling behaviors needs to be identified.

2.2 Essential Information for Open Building Remodeling Behaviors

To store the raw design data in RFID tags embedded, the essential information for open building remodeling behaviors needs to be identified. Once the essential information is embedded to the components via RFID tags, has the open building the self-data-providing ability, so that users can acquire the raw design data from the building for remodeling. However, due to the memory size limitation, all raw design information of a component can not be imported to one RFID tag. Accordingly, only numerical and few textual data essential to the remodeling behaviors can be stored in RFID tags, but the CAD or image files. The large documents can be stored in the database associated with components by key numbers. The essential component information respectively related to support and infilled systems were identified to import to RFID tags.

2.2.1 Essential information of support component

For the components of support system, the essential information related to the reanalysis remodeling behavior, was determined to store in RFID tags for enhancing the efficiency of structure reanalysis. To reanalyze structure safety for the conversion of an open building, the structure plan, relief maps, historical earthquake information, etc. as shown in Figure 2, need to input to the structure analysis software, such as SAP2000 and ETABS. However, due to memory limitation of the RFID tags, only the information related to the support component itself needs to be stored in the tags, so that the structure model of the open building can be generated in SAP2000 and ETABS in accordance with the acquired information of support components.

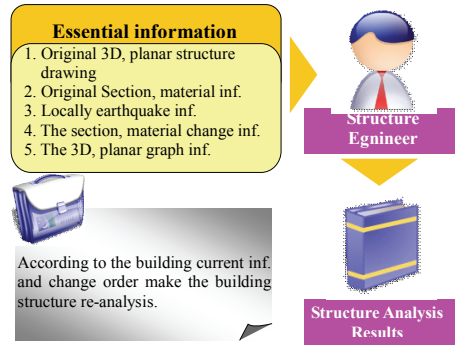


Figure 2 Essential Information for Support System Reanalysis

Moreover, in order to reduce the information volume, the numerical or textual design parameters of support components need to be derived from design drawings, so that parameter data can be stored in RFID tags.

Based on the schema of structure database in SAP2000 and ETABS, the information necessary to be stored in support component RFID tags were determined as Table 1 shows.

The essential data embedded in the support component RFID tags can be acquired with the RFID reader to import to SAP2000 or ETABS. Therefore, according to the imported component information, the structure model can be generated for safety analysis.

2.2.2 Essential information for infilled component

For the infilled system remodeling, the essential design information related to the redesign behavior

needs to be determined. Figure 3 shows the essential information for redesigning the infilled system of a open building.

Table 1 Data Stored in the Support Components

Attribute	Essential data of support component	
General	1. Project ID	
Material	2. Materials type 3. Component level 4. Section size 5. Weight 6. Length	7. Strength 8. Unit 9. Components type 10. Regulations
Position	11. Node i coordinate 12. Node j coordinate	13. Axes

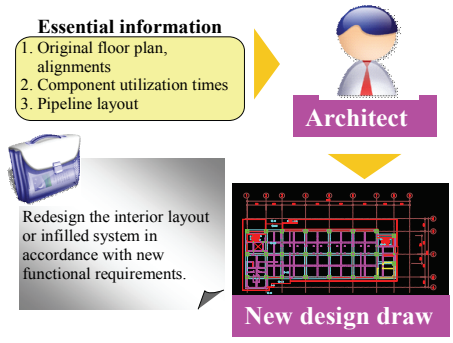


Figure 3 Essential Information for Infilled System Redesign

Similar to the data stored in the support component RFID tags, the design parameters of each infilled components were derived from the original design drawings as Table 2 shows. As the parameters are stored in RFID tags, architects can acquire the infilled system information to redesign the interior layout or infilled system of the open building.

2.3 RFID-based Information Management Mechanism for Open Building Maintenance

Since the essential information of support and infilled components were stored in the RFID tags embedded in the components, the RFID-based Information Management Mechanism was proposed to be the basis for developing the OBMIS. Three functional modules are included in the proposed mechanism, namely (1) support system information management, (2) infilled system information management, and (3) reanalysis/redesign modules.

Table 2 Infill System Necessary Data

Data attribute	Essential data	
General	1. Project ID 2. Manufactory	3. Constructor 4. Designer
Material	5. Materials type 6. Components layer 7. Section size	8. Weight 9. Unit 10. Components type
Position	11. Node i coordinate	12. Node j coordinate

2.3.1 Support system information management module

The support system information management module provides the functions to read, write, and update the components information within RFID tags embedded in support components. After acquiring all support components information as shown in Table 1, the structure engineers can redesign the structure plan for purpose conversions in accordance with the acquired information, and subsequently, the newly-design result can be exported to SAP2000 and ETABS for safety analysis. Meanwhile, as the open building is reconstructed based on the redesign results, system users can update the components' design parameters within the RFID tags. Accordingly, by using RFID-OBMIS, the support components design information can always be acquired/updated from/to the building components.

2.3.2 Infilled system information management module

Similar to the support information management, the infilled system information management module provides the functions to read, write, and update the components' design parameters within the RFID tags embedded in infilled components. However, since no redesign activity is necessary for infilled system remodeling (as shown in Figure 1), the acquired information is provided to architects for redesign the infilled system, but to export information to any external analysis softwares.

2.3.3 Reanalysis/redesign module

The reanalysis/redesign module provides structure engineers with the functions to export the acquired support components' design parameters to SAP2000 and ETABS softwares. Figure 4 shows the information transformation mechanism to

summarize the acquired components' information and transfer them to be input files of SAP2000 or ETABS softeares. Therefore, structure engineers can acquire structure information from building it self and export to structure analysis softwares for redesign and reanalyze newly structure plans for structure conversions of open buildings.

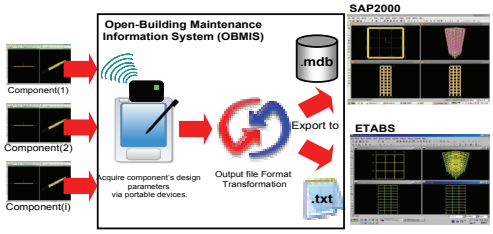


Figure 4 Support Component Information Transformation Mechanism of OBMIS

3. OPEN-BUILDING MAINTENANCE INFORMATION SYSTEM (OBMIS)

Based on the RFID-OBM, OBMIS was developed. Due to page limitation, only system runtime environment and the functions of read/write components information from/to tags, and export support system information to SPA2000 were illustrated.

3.1 Runtime Environment of OBMIS

Figure 5 shows the runtime environment of OBMIS. Since the OBMS adopts PDA portable device to acquire components information from the building (as shown in Figure 6), and store the data in the database server, two operation systems, namely (1) Windows Mobile 2003 and (2)Windows XP, provide different runtime environments respectively to PDA and database server.

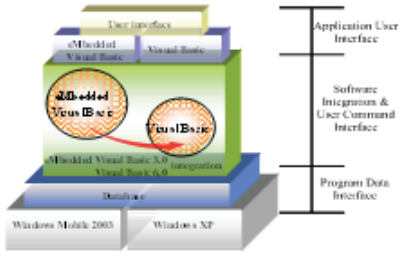


Figure 5 System Environment

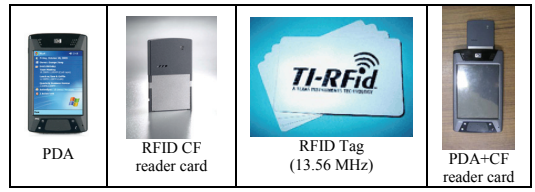


Figure 6 RFID Equipments for RFID-OBMIS

3.2 Read/Write RFID Tags

Accessing data from RFID tags embedded in the building components is the basic function of the OBMIS. By using PDA with RFID CF reader card (as shown in Figure 6), the origin data can be read from RFID-tags, and the newly-design parameters corresponding to one component cab be written to the specific RIFD tags associated with one unified identification (UID) number. Figure 7 and 8 respectively show the read and write functions of the client end user interface on the PAD.

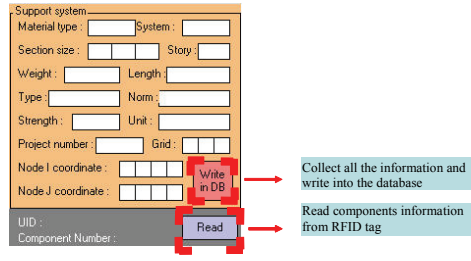


Figure 7 Read Tag Information from Support Components

3.3 Support System Information Exportation

All acquired components' design parameters will be stored in the back-end database server. Once all the design parameters of support system are acquired, users can export the support system information from database to a formatted output file. Two formatted output files can be generated by OBMIS, namely (1) SAP2000 database importation file and (2) ETABS importation text file. Figure 9 shows the exportation function of the OBMIS. Once the output file name is specified, the support system information is exported. The structure engineers can import the output file to SAP2000 for structure plan redesign and reanalysis.

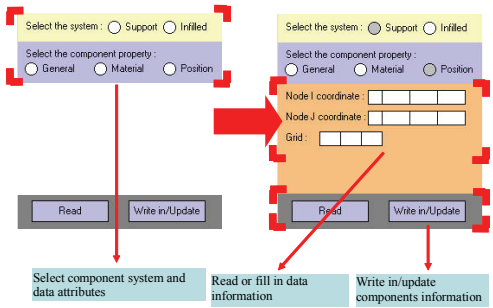


Figure 8 Write/Update Tag Information to Support Components

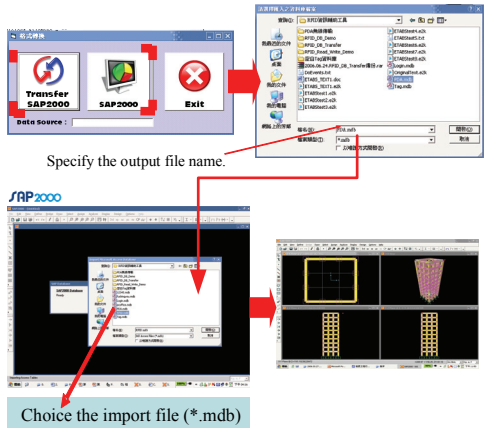


Figure 9 Export Support System Information to SPA2000

4. SUMMARY

To enhance the maintenance efficiency of open buildings, this study facilitated the idea of self-data-providing mechanism for open buildings by developing the Open-Building Maintenance Information System (OBMIS). To develop OBMIS, firstly, the idea of embedding RFID tags in support and infilled system components was addressed; sequentially, the RFID-based Open-Building Maintenance (RFID-OBM) model was proposed to determine the remodeling behaviors and required information in the open building maintenance phase. Therefore, as an open building needs to be remodeled, by using OBMIS, structure engineers can, in the one hand, acquire structure information by PDA device; once all the support system data is acquired, data can be exported to SAP2000 and ETABS for redesign and reanalysis; in the other hand, architects can acquire the original infilled components' data to redesign a new infilled system for purpose conversions of the open building.

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Construction Automation Group, I.I.T. Madras

AUTOMATED PROJECT SCHEDULE AND INVENTORY MONITORING USING RFID

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ABSTRACT

Automated project monitoring system has the potential to be effective in controlling project performance through continuous monitoring and control of the project in real time using Automated Data Collection tools. This paper presents a system that is designed to investigate the use of RFID for automated schedule and inventory monitoring in real time. The system considers the use of precast concrete or prefabricated steel structural elements like columns, beams, floor slabs and wall panels as building components. The building components are identified in real time through automated data collection using RFID technology. This RFID technology with other application software is integrated to identify the installed component and update the project schedule in MSProject and present the as-built progress status. The 3D model of the building which is also updated is visualized in AutoCAD. The construction industry response towards the use of the developed system is also reported.

KEYWORDS

RFID, Schedule Updating, Inventory Updating, Project Monitoring

1. INTRODUCTION

The effective control of construction projects depends on the monitoring, in which data are collected to analyze and report the actual project performance value, based on the schedule, cost, material consumption etc., This actual value is compared with the planned value to find the variances, based on which the control measures are taken to alter the performance in the future, to meet that planned value. Thus the project performance depends on the frequency of the feedback information (monitoring) and response (control) cycle. The limitations in the present system of project monitoring due to manual data collection and the delay in the reporting cycle causes delays in the response, which results in costly and complex measures to be taken to attain the planned performance level [1]. Therefore real-time data is needed for the control. This necessitates the introduction of automated data collection techniques in construction projects for effective monitoring and control in real-time.

The precast / prefabricated components life cycle consists of the manufacturing phase, construction phase and the maintenance phase. In the manufacturing phase, the details of the components' material composition during casting or fabrication should be documented. Data of where they are stored are to be documented to identify and transport them with minimum time loss. In the construction phase, the components delivered to the site have to be inspected and stored then installed. For this process the component has to be identified, located and tracked in the construction site. The fundamental function of field materials management is to assure availability of materials when they are needed for installation and make such availability information readily accessible for crew level work planning. Thus, underlying this functionality of field

materials management is the capability to track materials accurately and in a timely manner [2].

Finally details related to installation have to be recorded. In all these phases the real time data regarding the components identification, its location in the structure, details of installation are needed. Thus real time data is needed before and after the installation phase in case of construction projects using the precast / prefabricated components. This necessitates automated data collection not only for control but also for field material management.

One of the technologies that have been gaining significance as an automated data collection tool is the RFID technology. Radio Frequency Identification (RFID) refers to a branch of Automatic Identification Technologies in which radio frequencies are used to capture and transmit data [3].RFID technology can be used to identify and track labour / material or building components /equipment. This identification technique is used to identify and track the building components used in the site and the data collected in real time is converted using software technology for further use.

2. RELATED WORKS USING RFID

The NIST (2000) conducted the Comp-TRAK project, which attempted in identifying, locating and checking the position of steel members in the job site with reference to global positioning [4].It attempted automated tracking of the material from 'cradle to grave'. Akinci et al. (2002) analyzed the use of the RFID technology for tracking the pre-cast concrete members from the manufacturer to the installation site while storing their life-cycle information [5]. Yagi et al. (2005) proposed a Concept of "parts and packets unified architecture". Information related to a product is carried by product itself and can be handled to manage the whole system [6]. Song et al. (2006) determined the feasibility of active RFID to automatically track spool pieces and read additional spools' information during delivery and receipt processes [7]**.** Ergen et al. (2007) conducted field tests that demonstrated the basic feasibility of an automated system which integrates RFID and GPS technologies for tracking precast pieces in a storage yard [8].

The researches and pilot studies done using RFID technology have proved that RFID technology can be used to track materials / labour / equipment / components – precast concrete or prefabricated steel.

3. CONCEPT

The concept is based on the use of RFID in automating the data collection, integrating it with Precast/Prefabricated components, in locating these components during the construction phase, which is shown in Figure1.

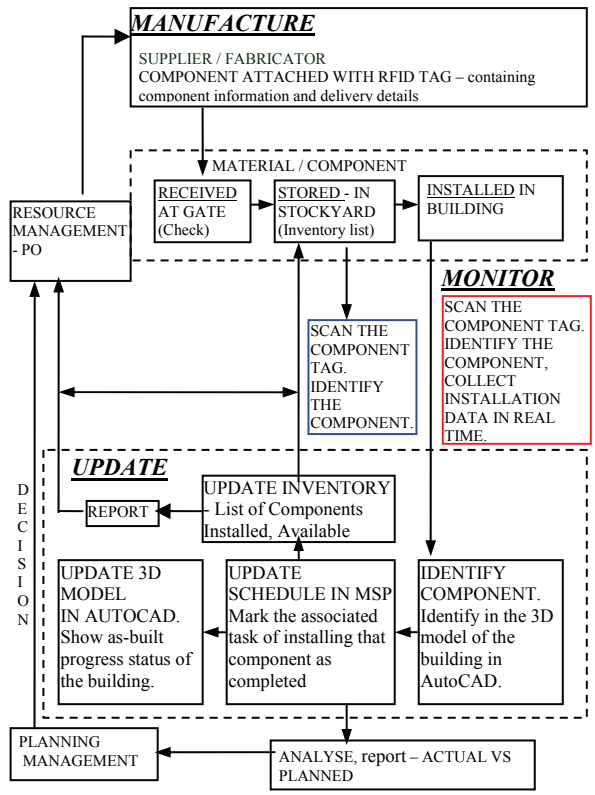


Figure 1 Concept

Based on this, the technology is utilized further to monitor the project progress.

4. SCOPE

The scope is limited to conducting the investigation at an experimental level, which uses scaled building model for the purpose. The RFID technology used for the system is 125 KHz passive system, which consists of a Hand Held Wand

Reader of read only type and tags of read only type.

The system considers the use of precast components or prefabricated components as building components. The components considered are such as the columns, beams, wall panels, floor slabs / floor decks that constitute the critical elements especially in pre-engineered buildings.

The time of scanning the component is considered as the actual completion of the associated task. This time is taken as the input for the system, and automatically entered as the actual finish time of the associated task.

The actual start time of the first task is assumed as the baseline start time of the task. The actual start time of the other tasks are assumed as the actual finish time of their corresponding predecessor task.

5. THE SYSTEM

The system consists of the Basic System components along with the Software Tool which forms the frame work for the System Architecture.

5.1 The System Architecture

Fig.2 depicts the system architecture. The program is done in the VisualBasic6 environment. MS Excel is used for the data base; AutoCAD is used for the 3D Model drawing and MSProject for scheduling.

The tag's identification numbers that had successfully communicated with the reader is used as the input. This is got via the serial port, transmitted from the base station reader and the transferred data is imported into the program. The user interface is a VB form.

5.2 The System Components

The system components are,

1. 3D Model of a Building in AutoCAD

A model of a building that is assumed to use precast / prefab components is designed. The 3D model of the building is done in AutoCAD. Each element of the model is identified with the component that could make up a precast/ prefab building.

2. The Schedule

The schedule is done in MSProject based on the designed 3D model.

3. RFID technology

Required RFID Specification:

Since the building model is done to scale, the read range required is less, i.e. within 100 mm. The reader required is portable type for easy handling, with tags of size within 20 to 40 mm so that they can be accommodated on the components of the building model. Since the read range required for experiment is lesser, passive technology is suitable, which offers the required read range. Additionally the components have only to be identified and so read-only tags are opted which can be read with a handheld reader.

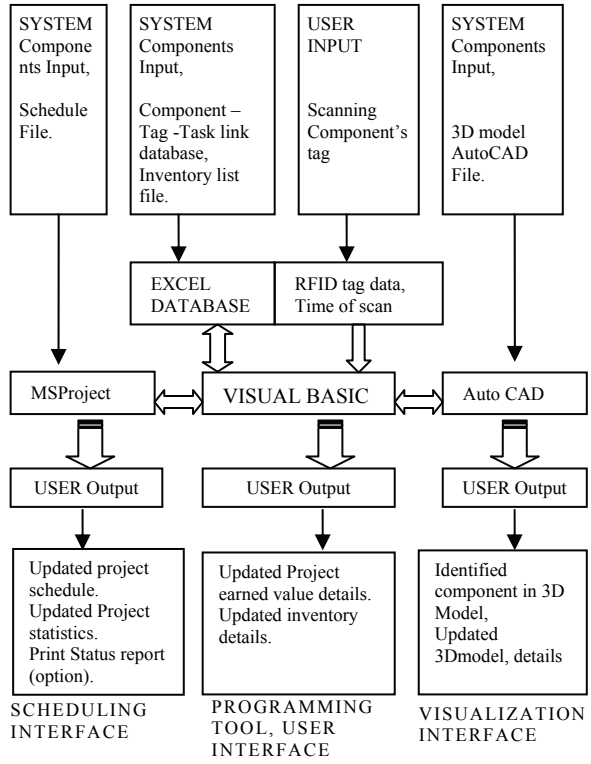


Figure 2 System Architecture

Selected RFID Specification:

RFID type: Passive System

Frequency: 125 KHz

Read Range: Approximately up to 50 mm

Tag: Passive read only type tag, 30mm Flexible Disc Tag in Polyurethane transparent package and data storage capacity of 10 unique hexadecimal characters.

Reader system: The reader system consists of the 'Hand held wand reader' (read only type) of 125 KHz frequency, which is connected to a 'Base Station Receiver'. This Base Station Receiver is connected to the laptop or PC serial port.

4. The Physical Model

The model of the designed building is fabricated to scale in wood as in Fig. 3. The components of the fabricated model can be assembled or dismantled. Each component of the model is attached with a tag that has a unique ID, which is used to represent the component's ID.

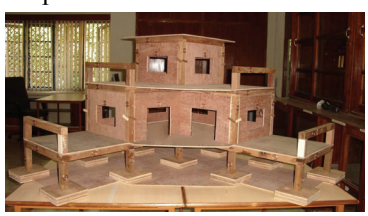


Figure 3 Fabricated Model

5. Inventory List

The inventory list in MSExcel contains the components under different categories that are available for assembling the building model.

6. Software Architecture

The architecture of the software tool is shown in Fig. 4.It consists of the input, the process and the output at macro level. The procedure is broadly divided into four phases.

In the first phase the program conducts the interrogation and the database query to authenticate the reading and retrieve the corresponding details from the database. The result of the query is displayed to the user, and used by the program for further application.

The second phase is the identification part. The program queries the database, identifies the component and displays it in the 3D model of the AutoCAD drawing file.

In third phase the program checks, is the installed component scanned already? And if the query is true then the user is asked to scan next component. Next it checks, is the predecessor of the component completed? And if the query is true the program proceeds further, else, the user is informed that the predecessor is not completed.

The fourth phase consists of the updating of the progress details in the schedule and inventory along with the 3Dmodel drawing, based on the data that is received into the program in the first phase. Thus the details of schedule are updated in the schedule file in MSProject, the status of completion is updated in the 3Dmodel, the inventory is updated in the excel file. Finally the project progress status is presented in terms of the earned value, variances in schedule and cost and the forecasting is given in the form of TCPI

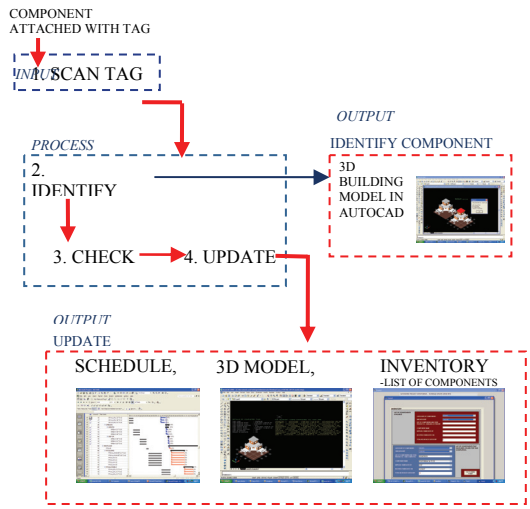


Figure 4 Phases in Software Tool

6. SYSTEM IMPLEMENTATION

For linking the AutoCAD 3D model components with the MSProject, the component name is assigned to the associated construction activity. Each of the component to be installed are assigned with the unique ID of a tag and also with the associated task ID which is selected from the list of tasks from the MSP file and these details are saved in an excel file. This excel file is used as the database to get the details of the component, tag and the associated task in the program.

The following steps explain the implementation procedure in detail.

a. Capturing Data from RFID Tag: First the component's tag is scanned. When the reader is activated, it sends RF signal to the tag attached to the component, and the tags' chip returns its unique ID to the reader. This unique ID is sent to the application device.

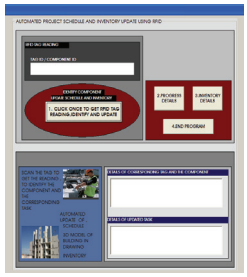


Figure 5 User Interface VB Form

b. Data Base Query and Presenting Details: The program begins following the successful reading of the tag .The clicking of a command button in the user interface which is a VB form as shown in Fig. 5, triggers the following events. The program captures the tag's data along with the date and time, authenticates tag ID and uses it to retrieve information from database about the component carrying the tag. The program identifies the component and presents the user, the details of the component and its related task details in the VB form.

c. Identifying the Component in AutoCAD 3D Model: Next, the user is presented with the AutoCAD drawing which shows the location of the identified component (where the component belongs to) in the building model as in Fig. 6. A message box gives the name of that component. In addition to that, the details like tag's ID, task's unique ID and task's baseline schedule details are also presented.

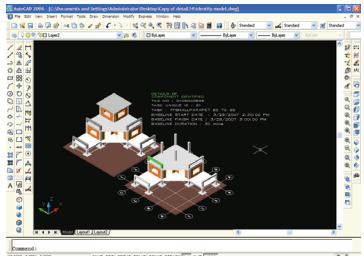


Figure 6 Visualize Identified Model

Then user is given a choice to update. The user could accept the option to update or deny and end the cycle of the program, and return to scan the next component.

d. Schedule Updating of Project in MSP File: In the next step, the schedule is updated after the program completes the checking. The program checks whether the task has already been updated or not, before opening MSP file, to avoid re-entering actual finish time. If component task has already been updated, a message warns that the task has already been completed. If the task is completed and schedule has not been updated the program proceeds to check if the predecessor tasks are completed or not. If predecessor is not complete, a message warns the user that the predecessor has not been completed. Else, if the predecessor is complete, the program proceeds further to update.

The Actual finish time which is the time of scanning the components' tag and the Actual start time (assumed) which is the actual finish time of predecessor task are entered automatically into the associated task's respective fields. When the actual finish time is entered, the task is marked as 100% complete. Tracking Gantt view of network is updated automatically as in Fig.7.

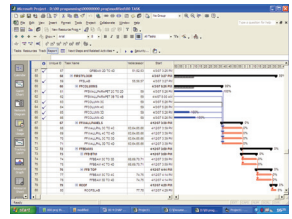


Figure 7 Updated Schedule

The user is presented with the project statistics and the option to print the project status report during the run time of the program. Finally the User is prompted to save the file. The user is also presented with the earned value method of project performance details in another VB form as in Figure 8.

e. 3D Model Updating in AutoCAD File:

The AutoCAD drawing is presented to user with the 3D Building Model which is updated based on the as-built progress. The updated 3D model view of the building is presented with the component that is installed then as in Fig .9. The program updates only after checking and confirming that the related task is updated in MSP schedule file.

Finally the user is prompted to save the file. The file is kept updating every time when the project schedule is updated.

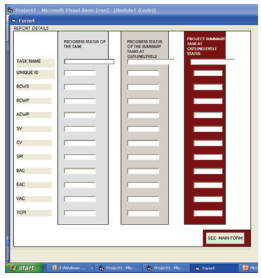


Figure 8 Project progress Details

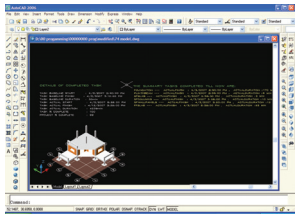


Figure 9 Updated 3D Model

f. Inventory Updating in Excel File: Updated details of the components that are available and that have been installed are presented to the user in another Form as in Fig. 10. The task is checked if it has been updated in MSP before updating the inventory file. If the query is true then the procedure for updating the inventory starts.

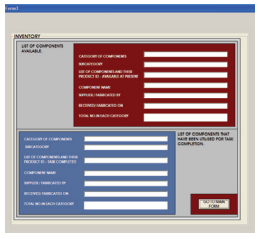


Figure 10 Inventory Update

g. End of the cycle and the program: Thus one cycle gets completed. The user is again presented with the main form to continue the program for next cycle. To begin the next cycle the user has to scan the next component and the click the command button to trigger the events. If the user wants to quit the program, the user can click the 'End' command button to invoke the event to end the program.

Benefits of the System

Direct benefits from the system can be categorized into,

Data collection -	Collecting Real time data.
	Accuracy and integrity in data.
Monitoring -	Reducing the manual paper work.
	Faster processing.
	Visualizing the stage of completion.
	Saving time by reducing the reporting cycle time.
	Decisions can be taken immediately.
Field material management -	Information regarding the inventory made readily available.
	Reducing time in locating components.
	Save time in identifying where the components belong to in the building.

and overall process change in field operation.

7. SYSTEM EVALUATION

The aim of this evaluation is to establish the usefulness and utility of the System at concept and application level and to indicate where changes to the system might be needed. Typical end users from industry and experts in Civil Engineering were asked to evaluate and give comments over the system.

In overall the users have not observed any major flaw in the system and accepted the concept with minor changes to improvise the system.

The limitations that were noted are,

The tasks other than those that involve building components are not considered.

The time of actual finish of the task depends on the time of scanning the tag of the component.

The actual start of the task is assumed as the actual finish of its predecessor, for which the program could be modified to get the actual start time.

8. CONCLUSIONS

The key conclusions are,

1. The System concept that is designed has demonstrated the utility of RFID technology for Automated Project Schedule and Inventory Monitoring in Construction Projects at an experimental level and thus the use of the technology in automated project monitoring along with material management in construction projects.
2. The System's architecture that is developed has the functionality which is required for utilizing the automated data collection technique using RFID with other application software, for the proposed concept.
3. The system concept developed is useful for pre-engineered construction, since the component could be tracked through the supply chain which has more advantages of combining, site material management along with monitoring project progress and performance control and with added advantage of giving information for maintenance, when read/write tags with high storage capacity are used. Thus usage of this system in pre-engineered structures construction offers the advantage of the system being both proactive and passive to enhance the total project performance. Hence, the designed system would be more suitable for pre-engineered structures than in-situ construction.
4. The limitation of using read-only tags is that the unique ID of each tag has to be linked to a data base to present other details. The passive tags read range was adequate for this system at experimental level. At implementation level, the RFID technology selected could preferably have read/ write tags along with read/write hand held reader, so the data can be directly written to it and utilized directly into the program and RFID technology which offer longer read range is preferable.

In Indian context, the awareness is increasing towards the use and benefits of the technology in construction for identifying components and storing their information in sites where bulk engineered materials are used. In future the new developments and thus the reducing cost of this technology could lead to increasing automation in data collection for field material management and project monitoring in real-time with reduction in cost of generating it.

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DEVELOPMENT OF CONSTRUCTION LOGISTICS SYSTEM USING RADIO FREQUENCY IDENTIFICATION

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ABSTRACT

The authors have developed a construction logistics system using a radio frequency identification technology for finely controlling several construction sites in order to improve the transportation and handling of construction materials. This system was experimentally applied to some small construction sites in the Tokyo metropolitan area for a few months twice, in 2005 and 2006. Through the two experiments, we applied the system to 26 kinds of 93 finish and equipment construction materials. This system comprises three items: 1) a distribution center, called the Logistics Service Center, for a lot of construction materials between construction sites and materials factories, 2) a Construction Logistics Control System via the Internet, and 3) a Construction Material Traceability Management System with radio frequency identification technology. From the results of the two experimental applications of this logistics system, we found the following: 1) carbon dioxide emissions from transportation vehicles were reduced by over 22 percent, 2) carbon dioxide emissions from the transportation vehicles to construction sites were reduced by 30 percent, and 3) the transportation vehicle loading rate was increased by 14 percent.

KEYWORDS

Logistics, Radio Frequency Identification, Supply Chain Management, Traceability

1. INTRODUCTION

In recent years, global environmental problems have worsened, and resources need to be recycled in order to create a sustainable society for maintaining economic development and the global environment. To construct such a society, it is important to manage information for recycling and reusing building materials, and to manage the circulation of materials from the manufacturing to disposal stages. However, in Japan, construction materials are typically ordered from the materials factory individually by each construction site, and then delivered from the factory to the site individually. Therefore, the loading ratio of transportation vehicles is low. The number and total mileage of vehicles could be reduced by improving the distribution efficiency, and this would also reduce carbon dioxide emissions from transportation vehicles.

The authors have developed a construction logistics system using a radio frequency identification technology for finely controlling several construction sites in order to improve the transportation and handling of construction materials. This system was experimentally applied to some small construction sites in the Tokyo metropolitan area for a few months, in 2005 and 2006. This paper outlines the system and the results of two experimental applications.

2. OUTLINE OF DEVELOPMENT

2.1. Background and Target of Development

It is important for improving the efficiency of distribution to consolidate distribution information [1], and to distribute the delivery demand in the mornings. Construction workers want to start working after carrying their materials in the

morning. As a result, each material factory must send many trucks carrying small amounts of materials to each construction site.

We focused on small- and medium-sized construction sites, aiming to create a system of continuously delivering materials from the material factory to the construction site, and to achieve the following:

1) Promote recycling of construction materials;

2) Reduce the carrying of surplus material to construction sites by distribution processing;

3) Reduce waste by accurately managing the amount of materials;

4) Reduce negative environmental impacts such as carbon dioxide emissions;

5) Organize materials etc. to improve the efficiency of delivery

2.2. Outline of Computer Management Tools

2.2.1. Joint delivery system

A joint delivery center (LSC: Logistics Service Center) is set up between the factory which produces the construction materials and the construction site. The materials are received with a heavy vehicle going round the factories as shown in Figure 1. Distribution processing such as unpacking, taking to pieces and piling up are executed at LSC. Joint delivery raises the carrying efficiency of the truck, thus reducing environmental impacts such as carbon dioxide emissions as fewer trucks are needed.

2.2.2. Construction logistics control system

This system enables logistics information to be shared among the materials manufacturers, contractors, and construction site offices via the Internet. As a result, the whole distribution plan can be optimized, and the efficiency of distribution and distribution management can be improved. Distribution plan information is transmitted to all project participants by mail via the Internet and cellular phone, and delivery is performed. Figures 2 and 3 show example screen displays of the system, which was developed based on the existing system [2].

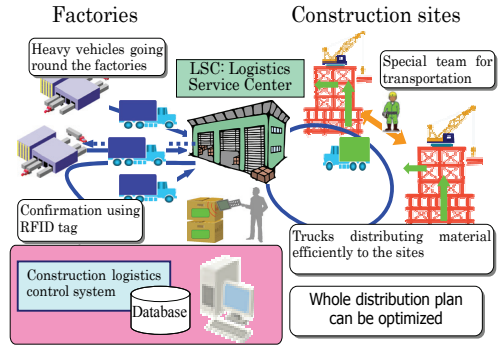


Figure 1 Outline of Construction Logistics System

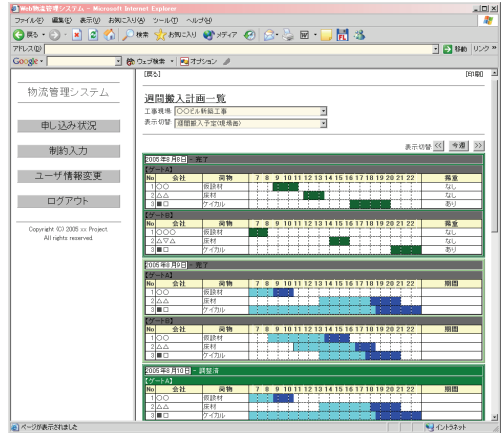


Figure 2 Construction Logistics Control System

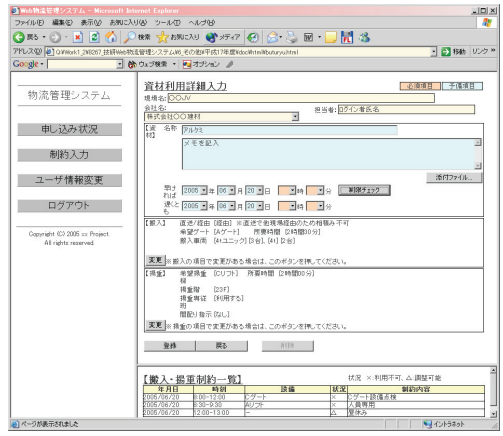


Figure 3 Construction Logistics Control System

2.2.3. Construction material traceability management system

This system is for inspecting the shipment of construction materials from LSC and checking their arrival at construction sites. It tracks the delivery status with RFID (Radio Frequency Identification) technology in real time. The RFID tag of "Unit of delivery" of the construction material or each "Unit of product" such as shown in Fig. 4 is installed, and delivery history information is then collected by the LSC and construction sites. RFID tags can use both an ultra-high-frequency and high-frequency band, because of restrictions on using RFID in Japan. It is necessary to accurately confirm whether to deliver materials to each construction site in order to go to more construction sites and reduce the load by joint delivery. Because data on the shipment and arrival of materials can be immediately known by using RFID tags, real-time delivery can be confirmed as shown in Fig. 5.

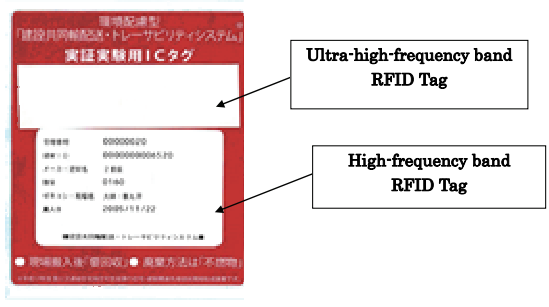


Figure 4 Radio Frequency Identification Tag

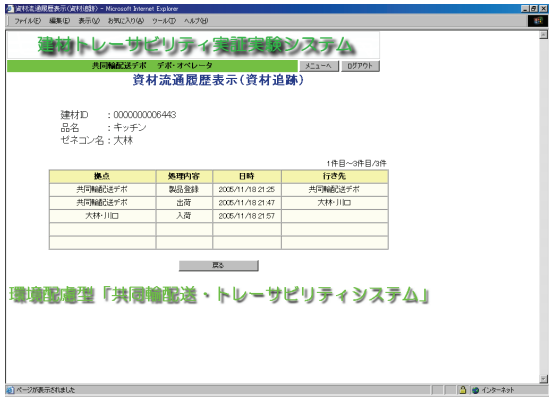


Figure 5 Traceability Management System

3. RESULT OF EXPERIMENTAL APPLICATION

3.1. Outline of Experimental Application

3.1.1. Time and construction sites of application

The joint delivery experiment in 2005 was conducted from October 24 to December 17.

Seven housing complex construction projects in the metropolitan area were selected for the experimental application, each with an average total floor of about 5,000 m^2.

3.1.2. Management of LSC and materials

LSC borrowed part of a warehouse of a delivery company located in central Tokyo (about 500 m^2) during the experiment. The information center for managing the information system and dealing with participants was established in the building with the warehouse. Personal computers and telephones/faxes were installed at the information center, which was staffed by the person in charge of the delivery plan and joint delivery/person in charge of the loading during the experiment period.

The delivery materials were 26 kinds of 93 finish and equipment construction materials such as exterior tiles, length scale seats, wallpaper, electricity, equipment, stone, lumber, floor material, and imported materials. These materials were sorted into one or two or more construction sites, were kept for a certain period such as the imported materials, were kits at LSC, and made the best use of the distribution functions of keeping, sorting, and distribution processing of LSC.

3.2. Preparation and Situation of Experimental Application

3.2.1. Joint delivery system

The stacking of materials and construction sites was promoted as shown in Photos 1, 2 and 3 to improve the distribution efficiency that was the main aim of the experiment. The stacking for two or more construction sites involved two types of delivery: different materials to the same construction site (photos 2 and 3) and different materials to different construction sites (Photo 1).

Photo 4 shows the stacking at LSC. Palettes and racks were used to effectively use the warehouse space.



Photo 1 Situation of Joint Delivery



Photo 2 Situation of Joint Delivery



Photo 3 Situation of Joint Delivery



Photo 4 Stacking Material at LSC

3.2.2. Construction material traceability management system

When the forklift passed the gate upon shipping from in LSC, the UHF band RFID tag was read with a pair of placed type readers shown in photo 5. Also, the truck driver from the LSC read the HF band (13.56 MHz) tag with a portable type reader when inspecting the construction sites shown in photo 6. After the RFID tags had been read at the construction sites, the driver detached it from materials and took it back.



Photo 5 Reading RFID Tag at LSC



Photo 6 Reading RFID Tag at Construction Site

3.3. Experiment Result and Consideration

3.3.1. Joint delivery system

Figure 6 shows the vehicle operation results for about two months. One operation is defined as going out from and returning to the LSC. The total number of such operations to construction sites was 127 times, and the maximum each day was eight times. There were three cases of joint delivery. The first case was to deliver two or more kinds of material to two or more construction sites. The second case was to deliver one kind of material to two or more construction sites. The third case was to deliver one kind of material to one construction site; this case was not joint delivery. The first case accounted for half of the total, and the second case for about 30 percent. The average loading rate of vehicles was improved by about 14 points by stacking and matching materials compared with about 70 percent and the conventional system. The number of vehicles entering the construction sites was reduced by about 30 percent compared with the conventional system. Moreover, the effect of using the LSC was high for materials containing many parts, because these could be made into a kit at the LSC.

The mileage of all vehicles was reduced by the higher efficiency of distribution, and carbon dioxide emissions from transportation vehicles were reduced by at least 22%, even though bringing together materials from the maker's factory in LSC with heavy vehicles was limited to just two months in this experiment and transportation was partial.

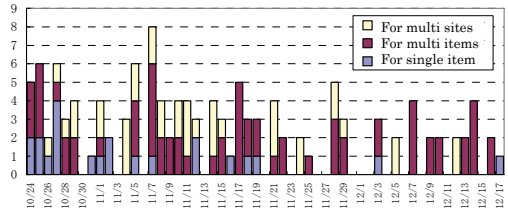


Figure 6 Operation Results of Transportation Vehicle

3.3.2. Construction logistics control system

The access log of the construction logistics control system was analyzed, and 45 users were found to have used it. The total number of logins was 1,237, and the maximum accesses each day was 70. The results are shown in Fig. 7 for accesses to the system. The number of accesses during regular working hours at the construction sites (8:00 AM to 5:00 PM) was 932, which was about 75% of the whole as shown in the figure. Access in the early morning and during the night (5:00 AM and 11:00 PM) became possible by using the Internet.

In this experimental application, it was important whether the delivery time could be adjusted by the LSC based on the transportation demand time. It is important in joint delivery how to allocate width (flexible time) to transportation demand. The result of the transportation demand time from the access log of the construction logistics control system is shown in Fig. 8. Event though some half the number of transportation demands became carrying at the specified time without the flexibility, the order that allows the flexibility of eight hours accounted for close to a quarter of the whole. In future, to increase the flexible time based on such data, we will consider incentives such as reducing the transportation cost.

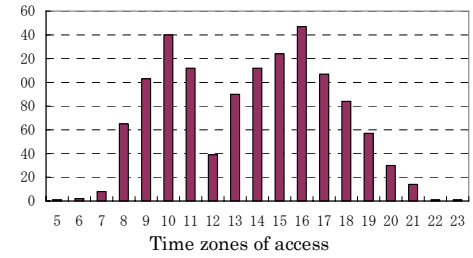


Figure 7 Access Time to Logistics Control System

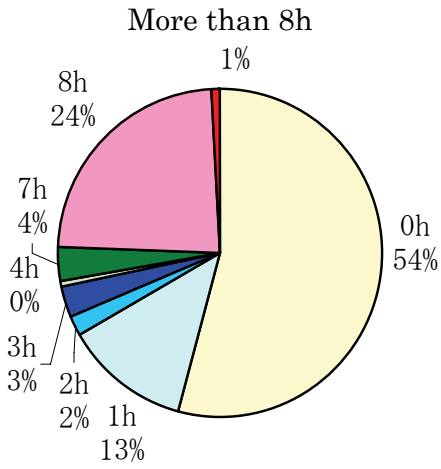


Figure 8 Width of Transportation Demand Time

3.3.3. Construction material traceability management system

This system was applied about one month after the LSC had been established. Previously, the LSC manager checked many kinds of material data, such as the name, product number, scheduled shipment date, delivery address, and amount. Especially, in the case of delivering two or more kinds of material to two or more construction sites, checking took 23 minutes. The work of inspecting construction materials upon shipment, including the above-mentioned paperwork, was decreased by about 1/3 by applying the RFID tags of this system.

4. PROBLEM FROM EXPERIMENTAL APPLICATIONS AND REMODELLING OF SYSTEM

4.1. Problem from Experimental Applications

4.1.1. Joint delivery system

The experiment was conducted for a limited period and at temporary LSC facilities, so there are some problems for the joint delivery system as follows:

- The change of the number of operations for transportation vehicles was large, and the storage space at the LSC, loading members, and equipment were excessive occasionally.
- It is necessary to clarify the cost allocation business model, contract, and method of adjusting joint delivery.
- Large construction sites are unsuitable for joint delivery.
- Some materials need special transportation such as by special vehicles.

It is necessary to secure more construction materials to solve these problems, by securing an appropriate number of construction sites and expanding the kind and amount of materials.

4.1.2. Two kinds of computer management tools

The issues for the two kinds of management tool, namely the construction logistics control system and construction material traceability management system, were as follows:

- Use by cellular phone is indispensable.
- The procedures became complex occasionally because the contract form was not changed.
- It was sometimes difficult to read the RFID tags stuck on some materials such as plywood and kitchen tiles, as shown in Photo 7.
- Readout is not possible if the forklift moves too fast.
- RFID tags became stuck at the LSC, so it took time.

As mentioned above, RFID tags have different readout rates according to the material and location where the tags are stuck. It is necessary to ensure that RFID tags at the LSC can be read by slowing down the forklift and so on.

4.2. Remodeling of Construction Logistics Control System

Most of the users of the construction logistics control system could not use the personal computer in the site office at any time because they are usually working outdoors, so there were strong demands for use by cellular phone. Therefore, a function was added as shown in Fig. 9.

- Reservation of delivery demand information and confirmation of delivery schedule



Leg of floor material



Wooden floor joist



Wallpaper



Furniture door

Photo 7 Example of Materials that were Difficult to Read

- Replenishment request of LSC to material factory
- Change in delivery schedule to construction sites

The input items of this system were limited so that everyone could use it easily. For example, the system sends a mail that requesting the users to make an input. The users can inspect the Web homepage automatically and directly upon receiving the message.

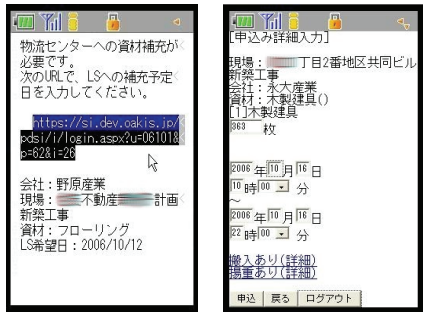


Figure 9 Example of Screen of Cellular Phone

5. CONCLUSION

We have developed a construction logistics system using a radio frequency identification technology for finely controlling several construction sites in order to improve the transportation and handling of construction materials. This system comprises three items: 1) a distribution center, called a Logistics Service Center, for handling many construction materials between construction sites and materials factories, 2) a Construction Logistics Control System via the Internet, and 3) a Construction Material Traceability Management System with radio frequency identification technology.

This system was experimentally applied to some small construction sites in the Tokyo metropolitan area for a few months, in 2005 and 2006. From the results of two experimental applications of this logistics system, we found the following: 1) carbon dioxide emissions from transportation vehicles were reduced by over 22 percent, 2)

carbon dioxide emissions from the transportation vehicles to construction sites were reduced by 30 percent, and 3) the transportation vehicle loading rate was increased by 14 percent.

Moreover, we solved the problems clarified in the experimental applications in 2005, improved the system and added a new function.

6. ACKNOWLEDGMENT

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Finally, we received cooperation from the manager of a general contractor and subcontractor, construction trader, materials manufacturer and delivery company in the experimental applications. We wish to express our gratitude to them all.

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MATERIAL TRACKER FOR CONSTRUCTION LOGISTICS

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ABSTRACT

It is necessary to manage materials (including prefabricated components) and identify their data communication process by collecting relevant information in real time for effective and efficient material management in construction projects. Recently, there have been many studies and developments using various wireless technologies including Radio Frequency Identification (RFID) for acquiring material information in real time in the construction industry.

However, since existing research project and developments on the application of RFID technology have focused on identification of material and monitoring its logistics by only using RFID technology, they have limitations on identifying material moving flow in logistics and tracking location in an accurate manner.

Therefore, the objective of this research is to develop a system that can identify logistics flow and location of construction materials with better performance by using RFID and wireless sensor networks such as Zigbee technologies. The system developed in this research is named as material tracker (MT), and its technical feasibility was verified through a lab test comparing with the existing tracking method using RFID technology only.

KEYWORDS

Material management, Logistics, RFID(Radio Frequency Identification),WSN (Wireless Sensor Network)

1. INTRODUCTION

The construction logistics is one of the significant management factors in order to proceed construction project. If materials which are needed in construction project do not supply in right place on time, it can make problems such as delaying schedule, increasing the cost of construction and reducing productivity. The identification of material, identifying materials moving flow in logistics and tracking materials location are needed for successful project management in construction.

Recently, many studies using Radio Frequency Identification (RFID) with specific materials such as concrete, structural steel works, finishing material, curtain walls, etc have tried for the collecting data of materials in real time and effective management. [2], [3], [5]

Furthermore, the study, the track of construction vehicle and location of workers, has been processed with GPS for location tracking and monitoring. In addition, the study, the location tracking of equipment, machinery, materials and other resources with RFID technology, has been tried. [1], [4], [5]

However, since existing research and developments on the application of RFID technology have focused on identification of

material. [2],[5]. In addition, identification of material with RFID technology is performed by human power. For that reason, not only are human power and time spent, but many errors are also occurred. And, there are some limitations such as installation of equipments, recognition in the shade, economical efficiency (high priced equipments) and management of supplying power (amounts of power consumption) due to the conditions of construction site such as vibrations and dust when using GPS for tracking location of materials.

This study considers WSN (Wireless Sensor Network) technology to overcome some limitations which are mentioned above.

WSN is a technique which can transfer automatically collected data by wireless in real time.There are the varieties of WSN technology such as Bluetooth, UWB and Zigbee. In particular, Zigbee, which is small, low price and low power consumption, does not need light-of-sight between nodes. And, it is possible to monitor tracking location of data through the specific ID of Zigbee.

Therefore, the first purpose of this study is to develop Material Tracker (MT) based on RFID and Zigbee technology for identification of materials, identifying its moving flow in logistics and tracking its location. And, its technical feasibility was verified through pilot test.

2. MATERIAL TRACKER

2.1 The Function of MT

The study is to develop Material Tracker (MT) in order to automate collecting data in materials, identify materials moving flow in logistics and manage tracking location based on RFID and Zigbee technology.

Developed MT recognizes the data of materials such as bulk and bundle type which is loading through RFID reader installed on MT and can check the flow and location of materials within the management of logistics through Zigbee in real time

2.2 Components of MT

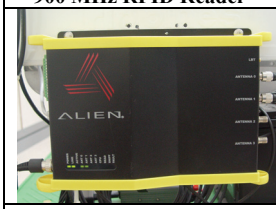
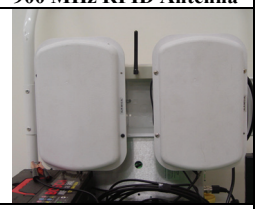
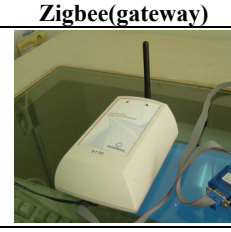
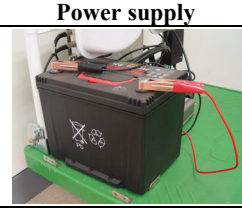
Material Tracker (MT) is consist of RFID reader which is in order to recognize RFID tag of loading materials, RFID antenna, Zigbee (sink node) which is for transmitting recognized data of materials to server, and power supply.

And, there are not only Zigbee, sensor node, has the data of location, but also Zigbee, gateway, receives the data of MT and then transfer it to server. Each function of equipments is as shown table 1



Figure 1 Material Tracker (MT)

Table 1 Details of the Function of Equipment

900 MHz RFID Reader	**900 MHz RFID Antenna**
	
function : Interrogating an RFID tag	function : Emitting radio waves
Zigbee(sink node)	**Zigbee(gateway)**
	
function : Passing data (Zigbee ID and Tag ID) to a gateway from sensor nodes	function : Receiving data (Zigbee ID and Tag ID) from a sink node
Zigbee(sensor node)	**Power supply**
	
function : Transmitting Zigbee ID to a sink node	function : Supplying power to each part of MT

2.3 Data Communication Architecture of MT

The structure of data for recognizing materials of MT and tracking location is as shown in figure 2. And following is explanation of data communication architecture of MT.

1) The data of materials attached RFID tag recognizes automatically through RFID reader which is installed on MT.
2) Zigbee(sink node) of MT receives the data of location from external Zigbee(sensor node) having the data of location and communication facilities.
3) Collected data of materials through RFID and location data by Zigbee is not only transferred to server throughout sink node of MT, but also monitored.

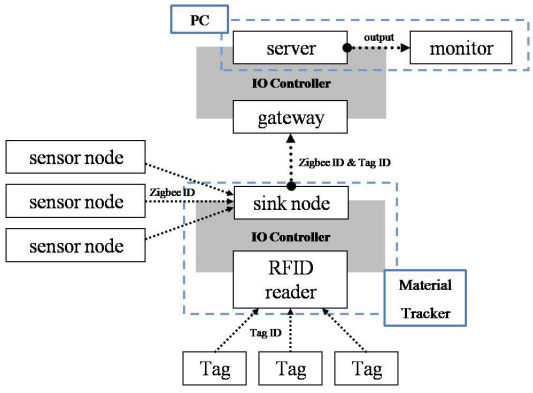


Figure 2 Data Communication Architecture

3. PILOT TEST

In this study, MT prototype based on the RFID technology and Zigbee has been developed. Moreover, technical feasibility of MT has been examined with pilot test.

The experimental set up and the results are as follows.

3.1 Overview of the Scenario for the Pilot Test

The variations of tracking location depended on the movement of MT and the function of recognizing location of MT located in a planned storage area have tested.

3.1.1 Test 1 (location tracking)

Test 1 is performed to examine the possibility of tracking location in moving MT. it is tested in office building due to the limitation of arrangement in construction site.

1) Sensor nodes, which have the data of location, are set up on the first floor to fourth floor and main gate of office building as shown in figure 3.
2) After carrying MT with material boxes attached RFID tags in building, MT has to be moved in each area.
3) Loaded material data of MT and location data of moving MT are monitoring throughout server.

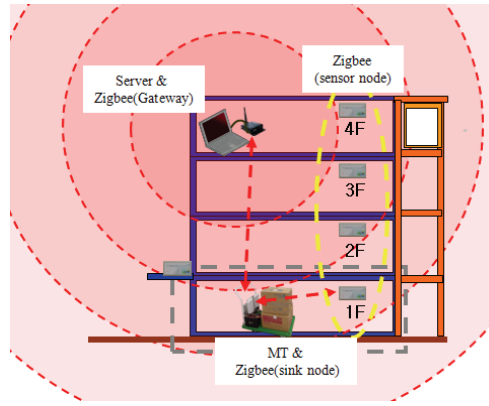


Figure 3 Test 1 Scenario

The status of installing sensor is as shown in figure 4.



Figure 4 Installation of Equipment

3.1.2 Test 2 (location recognizing)

Field test is performed in order to examine the localization of boxed materials in planned zones of the field by communication range of Zigbee nodes.

1) The communication range of the distance between each sensor node is set up as 30m. Thus, the distance between sensor nodes are increased to 80m in order to avoid the duplication of range, which is as shown in figure 5.
2) The sensing data of boxed material of MT and the sensing data of MT location in each zone are monitored throughout server.
3) The optimum distance for data communication is measured by moving MT within the communication range of Zigbee node which is set up in each area.

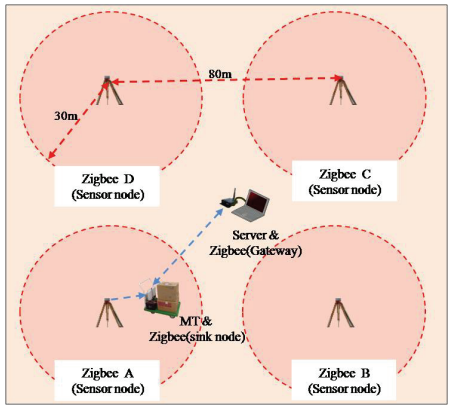


Figure 5 Test 2 Scenario

The status of installing main equipment is as shown in figure 6.



Figure 6 Installation of Equipment

3.2 Results and Analysis

The test results according to the experimental plans are as follows.

3.2.1 Test 1

Test 1 was performed five times over in total. As a result of test, when MT passed through the communication range of sensor nodes which are set up on on each floor, it was possible to recognize an accurate data of materials and location of MT through output data from server.

Output data of material and location of MT through the monitor of server is as shown in figure 7.

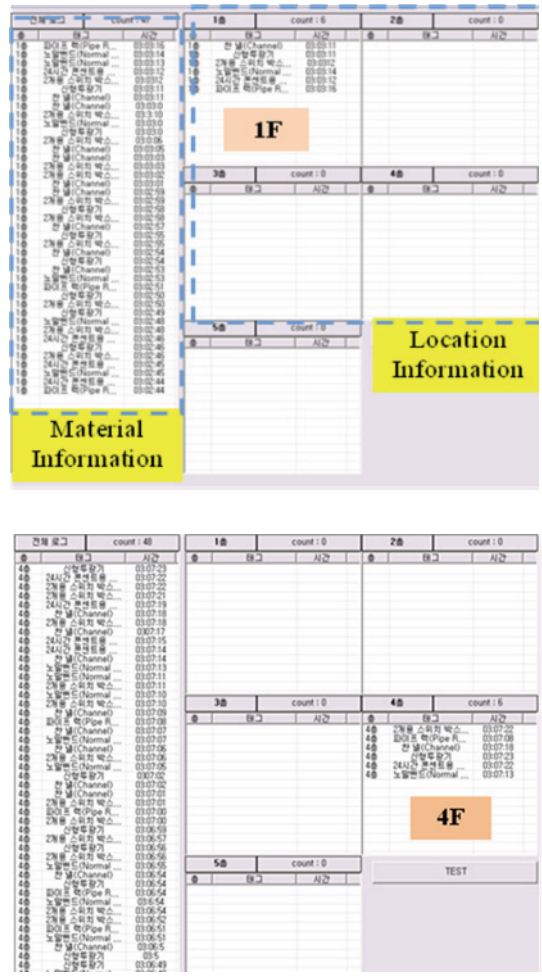


Figure 7 Data Collection

3.2.2 Test 2

Test 2 was performed five times over outside in total. As a result of test, the available commutation range between each sensor node and sink node of MT is as shown in table 2. In addition, the error in the communication range of the fixed sensor node is within less than 5m, which might be due to the environmental factors such as temperature and humidity.

Table 2 Result of Reading Range

	Case 1	Case 2	Case 3	Case 4	Case 5	Ave.
sensor node A	23m	28m	22m	26m	27m	25.2m
sensor node B	26m	26m	23m	27m	27m	25.8m
sensor node C	21m	24m	23m	24m	26m	23.6m
sensor node D	28m	29m	27m	29m	25m	27.6m

4. CONCLUSION

This study about development of MT integrated with RFID and Zigbee technologies to collect the data of materials and to manage the material moving flows in logistics of a construction site. We then conducted pilot tests in order to analyze any technological feasibility of the MT. According to the tests conducted, it was possible to recognize the location tracking within planned range through the movement of MT as well as in the stock yard.

However, it was not possible to collect data of any location exactly through sink node due to a interference when conducting the test in the stock yard with set of communication range of sensor node. Furthermore, it is limited that RFID reader clearly scans RFID tag data of the loaded material on MT but that fact was not considered to this test.

In the future in order to apply this automated tracking system to an actual construction project, it is necessary to find out ways to scan the data of materials completely using RFID reader.

Moreover, there is a need for finding out problems due to communication interference between Zigbee nodes. It is important to perform the test to check exact recognition range for tracking materials, which is able to improve to the efficiency of logistics management.

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Construction Automation Group, I.I.T. Madras

FIRE CONTROL IN BUILDINGS AND THE DEVELOPMENT OF RFID APPLICATION SYSTEMS

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ABSTRACT

Since Taiwan is a crowded island, serious disaster will cause personnel casualty and property damage. When calamity happens, how to effectively deal with the emergency is a significant task for the Fire Control Department. Currently the standard operation procedure for fire rescue is: (a) receives building fire report, (b) inquires available emergency rescue drawings, (c) asks for related drawings of the building. This procedure may waste precious rescue time, delay rescue effort and, even more, injure the fire fighters. In this research, PDA combined with RFID is used to develop the application package. This system will collect and return building rescue drawings and fire control information to rescue team in accident scene. This research can integrate the fire control related data, accelerate fire control operation, assist the responsible agency to manage the database and provide immediate inquiry capability through internet. Further, through RFID and PDA, the fire control data of a building can transmit immediately to the rescue team to carry out his mission effectively.

KEYWORDS

RFID, PDA. Fire Rescue, Building

1. REASONS AND GOALS

The traditional method for people to access previous fire control and disaster relief data archive files is both inefficient and time-consuming. To effectively shorten the time needed to proceed with relief efforts and increase the accuracy of the accessed data files, the planned goals for this study are as follows:

A. Obtain the A-type and B-type rescue diagrams and building fire control related data needed for "Standard Operations Procedures for Rescues in General Fires."
B. Establish various functional modules for "building fire control system mobilized identification system" through system analysis, and establish the database structure.
C. Establish an electronic database, which will provide for easy updating of data, increasing the effective management efficiency of related illustrations data, and combining PDA and RFID, achieving standardization, computerization, mobilization, and information integration in one consistent and integrated operation specification, thereby increasing rescue time efficiency, and decreasing the amount of damage caused by fires.
D. Combining PDA and RFID technologies, developing the "building fire control mobilized identification system", and managing the database through this system, thereby achieving the goal of making electronic data and improving the process of accessing this data so that the traditional inefficient paper-based methods will no longer be needed.
E. Verification of the feasibility and correctness of the system through case study, and the improvement of system defects.

2. FUNCTIONAL REQUIREMENTS

This entire "Research for the Mobilization of Fire Control in Buildings and the Development of RFID Applications" system includes the following items:

A. Establishment of the fundamental data structure of the system, and meeting user requirements.

B. Establishment of four main groups of system development requirements, which are: system operations, basic operations, building data operations, and data query operations.

C. System operations include user data management, authorization of parameter settings, and printer settings options. The main focus of this group will be on setting up the system environment.

D. Basic operations include city and county data management, township and municipality and area data management, and building type management. This group mainly establishes the basic area and locality information.

E. Building data operations includes building data management, single building query operations, various building floor and level data management, and the printing of building-related data. This group mainly sets up the basis for building data queries.

F. Data query operations include the query operations for the various floors of different buildings, query operations for the rescue diagrams for various floors of different buildings, building area query operations, and building type query operations. This group mainly deals with the establishment of rescue related information.

3. SYSTEM ARCHITECTURE

3.1. System Analysis

According to the functional requirements and user operation interface requirements for accessing fire scene illustrations and building related data obtained through the review of the data archives, we can develop a "Mobilized building fire control identification system" that is suitable for on-the-scene operation. By using data analysis technology to analyze operational procedures, simulate the relationship between the subsystem architecture and the database, confirm the necessary operations items, and eliminate unnecessary operational items, we can simplify system management operations, and produce an overall analysis on system security.

Table 1 System Modules

Operational Group	Operational Item
System Operations	User Data Management
	Authorization Parameter Settings
	Printer Settings
Basic Operations	County & Township Data Management
	Building Type Management
Building Data Operations	Building Data Management
	Single Building Query Operations
	Various Building Floor Data Management
	Related Building Data Printing
Data Query Operations	Data Query for Various Floors of Buildings
	Rescue Diagrams Data Query
	Building Area Query
	Building Type Query

3.2. Database Structure Analysis

The structure of the database is the primary core of the system. If the database structure is incorrect, or if it does not concur with user requirements, then the entire data stream will be erroneous, resulting in the output of unanticipated data. Thus, being able to devise a database structure that is concurrent with system functionality requirements is crucial to the success of the project.

With the advancement of technologies, database systems have evolved from traditional relational databases to object-oriented databases (OODBs for short), and object-oriented databases have already become the mainstream in database management systems. This study uses the ER/Studio tool to establish an ER Diagram, devises the data flow diagram according to this model and the user requirements, builds an E-R Model (Entity-Relationship Model), and then establishes the en-

tity database only after the various fields in the tables and the relationships between the various tables have been defined. This established database is the entity-relationship database.

After the user has established the ER/Model, the tools provided by the software can be used to convert the database structure into a script file that is compatible with generic database management systems, allowing the database console to read in the system database, its various table fields, the attributes of the various fields, and the relationships between the primary keys and the foreign keys of the various tables, thereby establishing the system database.

3.3. Establishment of Related Data

Through user requirement analysis, this study can clearly define the database to be established. The following is a brief description of the contents of the database:

A. Basic Operations

a. City and county data management: mainly establishes the data of various cities and counties to facilitate the setting of basic building data by administrators.
b. Township, municipality, and area data management: mainly establishes the data for various townships, municipalities, and areas to facilitate the setting of basic building data by administrators.
c. Building type management: mainly establishes type serial numbers and names for building types, for example, religious, public gathering, or residential buildings, etc.

B. Building Data Operations

a. Building data management: mainly establishes building serial numbers, building names, owners, emergency contact telephone numbers, owner mobile phone numbers, building latitudes and longitudes, building RFID label serial numbers, building types, and additional remarks data, etc.
b. Single building query operations: mainly establishes individual building information content, building types, and additional remarks, etc.
c. Various building floor and level data management: mainly establishes serial numbers for the various floors and levels of the buildings, renters, emergency contact methods, and notes, etc.
d. Printing of building-related data: provides users with printing of on-site query data.

C. Data Query Operations:

a. Query operations for the various floors of buildings: on-site users operate PDA query systems and send out information on various buildings through the RFID reader.
b. Query operations for the rescue diagrams for various floors of buildings: mainly establishes rescue illustrations for the various floors of buildings and provides users with query and access to these illustrations.
c. Building area query operations: categorizes buildings according to areas and then distinguishes them according to RFID serial numbers, allowing direct on-site query of information using PDA.
d. Building type query operations: performs queries and allows access through building serial numbers and building type names, such as religious, public gathering, residential buildings, etc.

3.4. PDA-End System Function Analysis

A. RFID Read Function:

Mainly provides a means for the on-site user to send or receive a message from the building's label through the read device. After the building serial number has been obtained, it is sent to the network server to proceed with building data query.

B. Building Information Query:

Provides users with a means for on-site building information query using the building's serial number as an index for performing the data query, including building serial numbers, building names, latitude, longitude, and floor levels, etc.

C. Geographical Information System:

When receiving building information through the wireless LAN, the user may select the floor level

of the fire through the system; to help the rescue operation after the information has been loaded.

D. Rescue Records System:

The fire control rescue records system provides fire scene records and information relative to the fire scene, and also transmits information back to the database for updating through the network.

4. SYSTEM FUNCTIONS

The following are the operations groups that this study has completed:

A. System Operations.
B. Basic Operations.
C. Building Information Operations.
D. Data Query Operations.

4.1. System Operations

The System Operations Module is divided into four pages: in addition to the basic printer, exit settings, and authorization parameter settings, it also includes User Data Management.

Six user authorization levels (Entrance, Edit, Insert, Print, Delete, Other) can be set for user data management; and the display information and display ratio of the illustrations can be specified through the parameter settings.

4.2. Basic Operations

Included in the basic operations are: County & Township Data Management (Figure 1), Municipality and Area Data Management.

4.3. Building Information Operations

The building data operations system includes: Building Type Management, Single Building Data Operations (Figure 2), Various Building Floor Data Management, and Related Building Data Printing.

4.4. Data Query Operations

The data query operations system includes: q Data Query for Various Floors of Buildings (Figure 3), Rescue Diagrams Data Query, Building Area Query, and Building Type Query combined with RFID.



Figure 1 County & Township Data Management

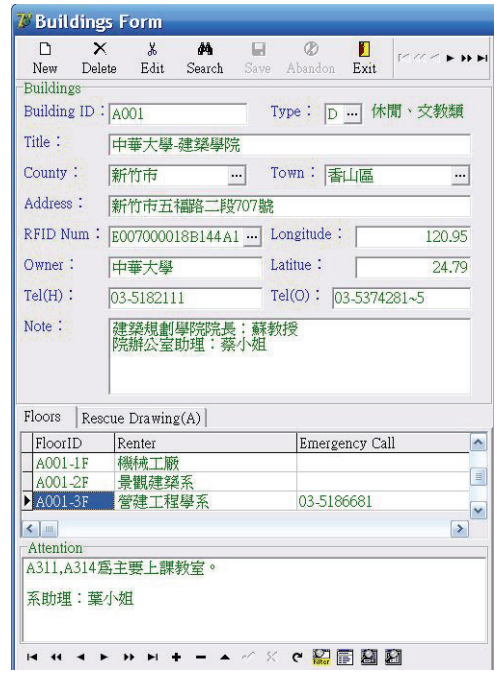


Figure 2 Building Data Input Dialogue

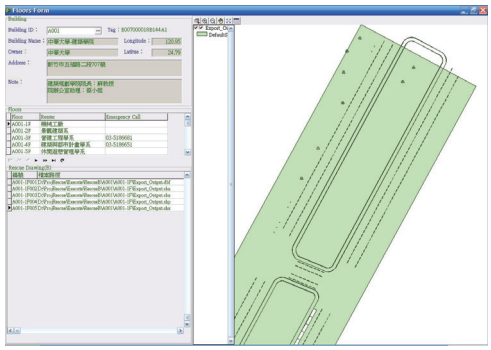


Figure 3 Loading of Illustrations Data for a Specific Floor Level

4.5. Application of RFID and PDA

A. Design and Planning of System Forms

This portion will focus on database data fields and the operational display of the PDA as the basic elements for form planning, and will take the user's operational requirements into consideration for the design.

B. Establishment and Operation of the System

a. RFID Label Reader Function

Primarily provides on-site users with a means of sending a read message to the building's label through the reader card. After the serial number of the building has been obtained, it will be sent to the server to proceed with queries of building related data, such as building number, name, geographical location, etc.

b. Geographical Information System

Through the included Superpad function, the on-site user can directly proceed with the query, creation, deletion, modification, and measurement of building illustrations, updating the illustrations instantly, and thereby ensuring that the illustrations are as up-to-date and meaningful as possible.

4.6. User-End System

A. Building Label Identification

Using the RFID read function for building label identification. First, select the connection port and verify whether or not the CF-Reader has successfully connected, as shown in Figure 4.

B. Building Data Query

This sends the building serial number to the dynamic data webpage to proceed with data query, as shown in Figure 5.

C. Various Floor Level Information Query

This proceeds with query of the data of various floors through relative menu selection, as shown in Figure 6.

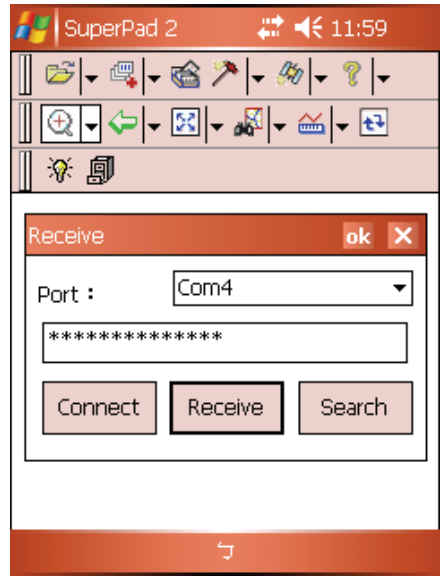


Figure 4 Reading of Building Labels

5. CONTRIBUTIONS

By going through archives and research papers, this study has obtained knowledge and understanding of the principles and applications of current RFID technology and the information needed on-site at building fire disaster scenes, and has proposed recommendations and strategies regarding the manual review of illustrations at these disaster sites. This study has also proceeded with system analysis and database establishment according to current PDA, RFID, and GIS technology applicability, and has established a "Mobilized Identification System for Fire Control in Buildings", with the goal of creating a mobilized querying platform for building fire control rescuers.

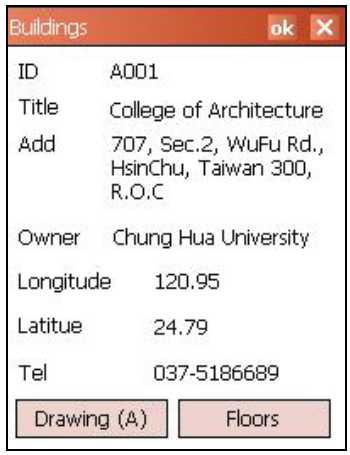


Figure 5 Query of Building Information

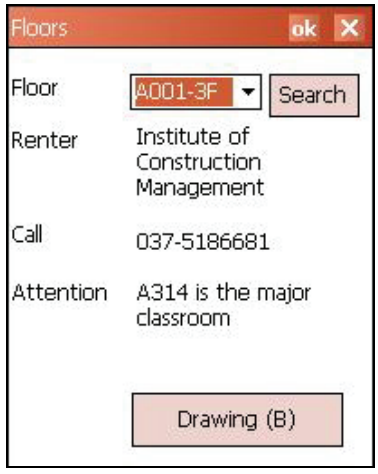


Figure 6 Query for Data from Various Floor Levels

By establishing the "Research for the fire control in buildings and the development of RFID application systems" in this study, the following contributions can be made to domestic fire rescue operations:

A. Relative "Standard operation procedures for general fire emergency incident rescue operations" data and illustrations that must be accessed will be collected and stored and managed electronically, making the data less susceptible to loss. Integration of PDA and RFID will rationalize, standardize, computerize, mobilize, and integrate information into a single consistent and streamlined operation, increasing the available rescue time in domestic fire emergency rescue scenes, and decreasing the damage resulting from such disasters.

B. Establishment of a comprehensive database system, taking advantage of wireless PDA transmission systems to directly transmit rescue diagrams and illustration data related to the particular fire scene, thereby providing instant, rapid, and accurate query of relative data, boosting rescue efficiency and time-effectiveness, and preventing any impact or errors resulting from human error.

C. Conversion of the rescue diagrams and illustrations from paper-based documents to electronic files, thereby achieving rationalization and standardization, which will in turn boost overall computerization, systemization, and networking, which will further reduce required human resources and cut costs.

6. ACKNOWLEDGMENT

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 95-2622-E- 216-008-CC3.

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DEVELOPMENT OF A PROBABILISTIC SENSOR MODEL FOR A 3D IMAGING SYSTEM

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ABSTRACT

The use of high frame-rate 3D imaging systems for construction equipment control is part of a broader research effort at the National Institute of Standards and Technology investigating innovative technologies for automated construction, performance and evaluation of 3D imaging systems, and construction object recognition and tracking. A probabilistic measurement model is desired for these imaging systems to better understand and describe the instrument performance, and to create synthetic data sets for algorithm development, training and testing. The initial development of a probabilistic sensor model and 3D image simulator based on an open-source graphics package is presented in this paper.

KEYWORDS

3D Imaging System, Flash LADAR, 3D Range Camera, Sensor Model.

1. INTRODUCTION

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. Research efforts in this project have produced an automated construction testbed that includes a 6 degree-of-freedom robotic crane (the NIST RoboCrane), laser-based real-time tracking, ultra-wide band (UWB) tracking, radio-frequency identification (RFID), and both high-resolution and high-frame rate 3D imaging sensors (i.e., construction-grade laser scanning and range cameras)[1].

An initial demonstration project involved autonomous assembly of a multi-component test steel structure using the robotic crane with pose tracking provided by a laser-based site measurement system and assembly scripts generated from a commercial 4D CAD package. More recent work includes the addition of a prototype site visualization system – JobSight – that allows monitoring of site sensor data, the current position and planned action of robot agents, and other object data such as CAD models, point clouds, etc. Figure 1 (a) and (b) depicts RoboCrane and JobSight, respectively. Additional information can be found in [1].

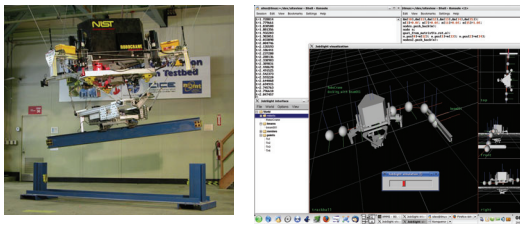
In the first demonstration project, there were no exteroceptive sensors[2] mounted on the crane. The next effort involves the use of a high-frame rate (approximately 30 Hz) low-resolution (160 pixels x 124 pixels) 3D imaging system (range camera) as an obstacle avoidance and docking sensor

[1] Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

[2] A newer model of this range sensor is available. Examination of the next-generation sensor is an element of future work

Target recognition objects are structural steel elements.

In probabilistic robotics, a percept action is characterized as arriving at a conclusion about the world given a sensor measurement, a measurement model, and prior state information. This problem is usually not directly solvable, and instead Bayesian inference is applied to produce the best estimate of the solution given a certain sensor model. The initial development of a range camera sensor model to use in 3D construction object recognition and tracking is the focus of this research project.



(a) (b)

Figure 1 (a) RoboCrane Carrying Element of Test Structure and (b) Screen shot of the Job Sight visualization software

2. RELATED WORK

Zheng et al. [2] present a flash LADAR (laser detection and ranging) object-recognition system which fit 10 pixel x 20 pixel range images to a template generated from a laser physics based simulation. The algorithm used a projection-based filter to trim the candidate pool and then used both pixel matching (shape) and silhouette matching (boundary) for recognition. The system was trained using synthetic image data for seven military vehicle targets developed from a LADAR simulation package.

The use of commercial models and commercial graphics animation software for developing automatic target recognition algorithms is discussed in [3]. The use of the open source Persistence of Vision raytracer (POV-Ray) [4] and the unofficial MegaPOV extension [5] to develop 3D data for generating and testing 3D video communication systems is reported in [6], though implementation details are not provided. An example of a high-fidelity, physics-based LADAR simulation environment used for hardware design is provided in [7].

3. MEASUREMENT MODEL

3.1. Terminology

The following terms are provided as a basis for communication within this paper.

Range uncertainty: The uncertainty associated with a distance measurement reported by an instrument to a given object of interest (or target). Uncertainty is a parameter that characterizes the dispersion of the measurement values that could reasonably be attributed to the measurand. Range uncertainty for active 3D imaging systems varies as a function of target range, target reflectivity, target angle of incidence, and sensor azimuth.

Beam spot size: The size of the light or laser beam as it hits a plane perpendicular to its travel path. Because of beam divergence, the beam spot size is dependent on, and should specify, the distance beween the target and the beam source. For example, the beam spot size is 50 mm at 100 m.

Mixed pixels: Errant 3D data resulting from the way most instruments process multiple returns. These multiple returns occur when a laser beam hits the edge of an object and the beam is split. In this case, part of the beam is reflected by the object while the other part continues and may be reflected by another object beyond. The measured reflected signal therefore contains multiple range returns, and typically the reported range measurement for that particular ray vector is an average of those multiple returns.

3.2. Sensor Description

The range camera used for these experiments is a commercially available, phase-based AM-homodyne device that uses a bank of 870 nm IR LEDs (infrared light emitting diodes) for the illumination source. The source is modulated at 20 MHz, yielding an unambiguous range of 7.5 m. The focal plane array (FPA) is 160 pixels x 124 pixels with a corresponding nominal field of view (FOV) of 43° (h) x 46° (v). Data returned from the device include range, intensity, and amplitude per pixel at a frame rate of approximately 30 Hz. Settings for the integration time, amplitude

threshold, and distance offset are user-controlled. The sensor is shown in Figure 2.

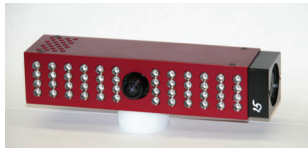


Figure 2 The Range Camera

A summary of manufacturer's specifications is provided in Table I.

Table I Manufacturer's Specifications

ATTRIBUTE	VALUE
Frame Rate	30 Hz
Range	7.5 m
Resolution	< 1 cm
Field of View	43˚ x 46˚
Pixels	160 x 124

3.3. Sensor Evaluation

The instrument range uncertainty was determined as described in [8]. Measurements of an 18 % reflectivity, 40.5 cm (16 in) x 25.4 cm (10 in) planar target were taken at ranges of 1 m through 7 m at intervals of 1 m, at a zero angle of incidence. All tests were conducted indoors under ambient lighting (fluorescent) conditions. Ranges to the targets were measured using a laser distance meter with an uncertainty of ±1.5 mm (1σ) mm over a range of 0.2 m to 200 m. At each range N = 1000 images were obtained and range data were sampled from a 7x3 pixel region at the center of the targets. The sampling was repeated two additional times at each range for a total of three sets per range increment. The results of the range error measurement are shown in Figure 3.

All samples are with the target angle of incidence = 0° and target reflectance = 18 %. There are three sets for each range increment. Plotted points are offset slightly for visibility. Error bars indicate uncertainty (± 1 σ).

Although there is an oscillatory behavior to the mean range error, for simplicity in this first iteration of the sensor model the error is fit as a linear function given by:

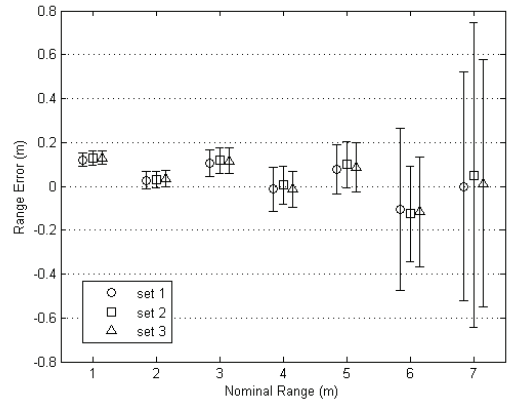


Figure 3 Range Uncertainty test results for N=1000 image samples and 7x3 pixels sampled per range image.

$$\mu_{Error} = -0.027R + 0.16 \quad (1)$$

where

μ_{Error} = mean range error

R = range

The standard deviation of the range error σ_{Error} is given by:

$$\sigma_{Error} = 0.0025R^4 - 0.031R^3 + 0.13R^2 + 0.22R + 0.14 \quad (2)$$

3.4. Sensor Model

Thrun et al. [9] presented a probabilistic measurement model of a beam finder that is a mixture of four types of errors. This mixture model includes:

(1). Normal distribution of a correct range measurement with noise

(2). A uniform distribution at the max range of the sensor for a failure to intersect any objects

(3). An exponential distribution for shorter than expected range measurements due to unexpected objects

(4). A uniform distribution over all ranges for random returns.

Figure 4 is a representation of the four-component measurement model. Of note, only components (1) and (2) of the mixture model were incorporated

into the synthetic data generator[3]. Components (3) and (4) require additional experimental data.

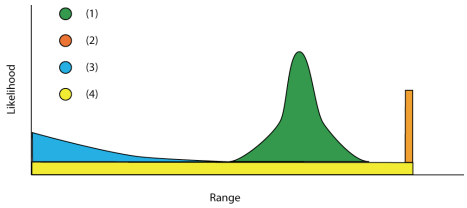


Figure 4 The Sensor Model (adapted from Thrun et al.)

4. SYNTHETIC 3D IMAGE GENERATION

4.1. Motivation and Design Criteria

A system for generating synthetic 3D image data from CAD models is needed to systematically evaluate and test various algorithms for model-based construction object recognition and tracking research. The ability to vary the noise levels in the synthetic data and generate representative noisy data sets would not only significantly aid in algorithm development, but would also provide data-driven recommendations to manufacturers for future system requirements.

The primary performance criterion for the system was the ability to generate 3D image data from CAD models that was representative of the type of data that would be provided from the tested instrument. Specifically the FOV (field of view), range, and pixel field had to be consistent with the range camera parameters. The mean range error and variance (both as a function of range) also had to be incorporated into the system model. Finally, the ability to simulate the mixed pixel effect was highly desired, as this is a significant contributor to the system noise.

4.2. Implementation

The system consisted of four basic elements: a scene generator, a raycasting function, a Monte Carlo simulation for generating modeled noise, and a mixed pixel simulation. In all cases, specific efforts were made to use existing software to meet base-level capabilities where available.

MegaPOV (an unofficial modified version of POV-Ray) was chosen as the raytracing application. POV-Ray is an open source raytracer with a large community following. MegaPOV is an extension of POV-Ray with numerous post-processing features, one of which is the creation and storage of a depth map from the ray trace data. Unfortunately, the depth data from MegaPOV only provides 8-bit resolution (e.g., ≈ 3 cm for 7.5 m). VLPov [10], which is an annotation patch developed at UCLA for MegaPOV, was used to provide increased depth resolution. The VLPov package also provided MATLAB scripts for reading and processing the depth map data. The disadvantage of using the VLPov patch was that it necessitated recompiling MegaPOV and prevented the use of the application's graphical user interface.

The CAD scene was generated using a commercially available software package that could export to the POV-Ray scene description format. Of note, this is a common capability with most current CAD packages. The camera parameters in the scene description file were then manually edited with the range camera parameters. The desired resolution was set with an initialization file. In this case, a resolution of 804 (width) x 624 (vertical) was used. This was a fivefold increase in the resolution required for single raycasting (160 x 124) and allowed the use of a 9 x 9 kernel to simulate the beam spot size.

The binary depth map resulting from the MegaPOV rendering was read and initially processed with the VLPov Matlab files. The depth matrix was then modified to represent the max range effect by substituting 7.5 m for all pixels without object intersections, and then reduced to 160 x 124 using the kernel (in this case using an equal weighting from each of the 81 rays). This averaging of the rays produced a rudimentary mixed pixel effect.

The data were then adjusted with additive Gaussian noise using the mean error (1) and standard deviation (2) functions derived from experimental data. The resulting point cloud was then imported to the original CAD package for viewing and comparison with the original model.

[3] Since the range camera is a phase-based system with only one modulation frequency, there is the additional factor of errant range returns for objects greater than the unambiguous range (7.5 m) of the system. This effect was not modeled

4.3. Sample Data

Sample data sets were generated using a CAD model of an existing 3D imaging artifact that is used in testing the performance of different 3D imaging systems. The star artifact is shown in Figure 5.

The CAD model was rendered using the synthetic 3D image generator, and point clouds were produced with the following parameters:

(1) Single ray for each range element – no noise

(2) Single ray for each range element – with noise

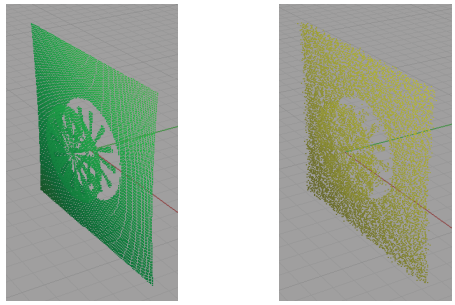
(3) Multiple rays (81) for each range element – no noise

(4) Multiple rays (81) for each range element – with noise

Figures 6 through 8 depict the point clouds generated from each of those parameter settings.

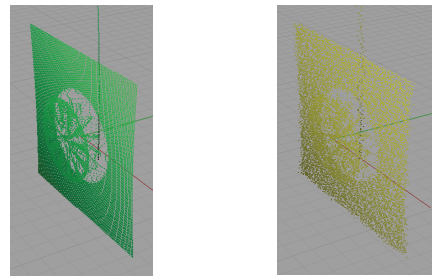


Figure 5 The Star Artifact



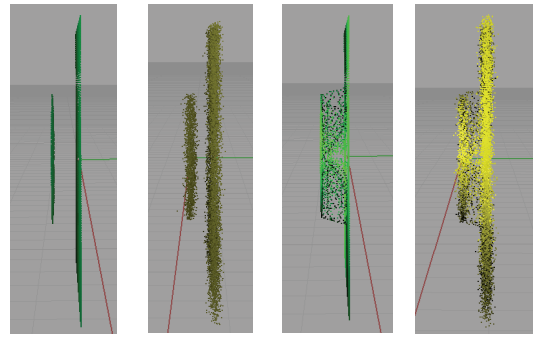
(a) (b)

Figure 6 Star Artifact at 2 m from Range Camera, Single Ray for Each Range Element, (a) No Noise, (b) Noise



(a) (b)

Figure 7 Star artifact at 2 m from Range Camera, Multiple Rays for Each Range Element, (a) No Noise, (b) Noise, (note mixed pixels between star and wall)



(a) (b) (c) (d)

Figure 8 Star Artifact (profile) at 2 m from Range Camera, Single Ray for Each Range Element, (a) No Noise and (b) Noise Multiple Rays for Each Range Element, (c) No Noise and (d) Noise

5. CONCLUSION

This report presents initial results in the development of a probabilistic sensor model for a high frame rate, noisy, 3D imaging system. A synthetic 3D image generator based upon open source raytracing software is also presented. From a visual inspection, the point clouds appear representative of the types of data sets one would achieve from the actual instrument, though thorough validation testing is required. The validation testing will be conducted as part of future work.

6. FUTURE WORK

Recommendations for future efforts include the following:

- Validate synthetic imagery against real data.
- Investigate different kernels and raycast oversample sizes for generating mixed pixel effects.
- Repeat range uncertainty experiment and model development for third-generation sensor (second-generation reported in this paper).
- Develop data sets of various steel beam configurations for object recognition research.

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EVALUATING A RANGING PROTOCOL FOR 3D IMAGING SYSTEMS

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ABSTRACT

In 2006, the ASTM E57 committee was established to develop standards for 3D imaging systems. A 3D imaging system is a non-contact instrument that is used to measure the range and bearing to and/or the 3D coordinates of points on an object or within a region of interest. A draft protocol to evaluate the range error in these systems was proposed. Two rounds of tests were conducted in 2007 to evaluate the ranging protocol. The evaluation of the protocol revealed that it was impractical to test the proposed 60 combinations of factors due to the length of time required. However, sixteen combinations using planar targets can be completed in one day. Measuring the "true" distance from the 3D imaging system to the targets was performed using a laser tracker during the first round of tests and a total station during the second round. The procedures for these measurements as well as the interaction between the main factors need further consideration.

KEYWORDS

3D Imaging Systems, ASTM E57, Laser Scanning, Ranging, Standards, Test Protocol.

1. INTRODUCTION

In June 2006, the ASTM Committee E57 on 3D imaging systems was established. A 3D imaging system is a non-contact instrument that is used to measure the range and bearing to and/or the 3D coordinates of points on an object or within a region of interest. The specific type of systems E57 is initially focusing on are laser-based, time-of-flight systems, which are also often referred to as laser scanners or LADARs (laser detection and ranging).

A subcommittee, E57.02 - Test Methods, was formed to develop test methods to evaluate these systems. A draft protocol to evaluate the range error was proposed. This draft ranging protocol was developed based on input from a series of workshops on 3D imaging systems held at the National Institute of Standards and Technology between 2003 and 2006. Some initial concerns with the protocol included the overall time required to complete the testing, support equipment requirements, and data analysis methods. In order to better understand the challenges of conducting the range testing as proposed, an evaluation of the protocol was necessary. This paper briefly describes the ranging protocol and the preliminary findings of challenges encountered.

2. RANGING PROTOCOL

The draft ranging protocol is described in detail in [1]. In brief, the protocol seeks to evaluate range error as a function of four factors - distance, target reflectivity, angle of incidence (AOI), and azimuth angle. At the NIST workshops, these factors were identified as being the major sources of range error.

The draft ranging protocol proposed to vary the above factors as follows:

Distance (from instrument to target) - 5 levels, $D_1,\ldots, D_5$:

– smaller of ($10\ \% R \leq D_1 \leq 20\ \% R$) or 30 m

– smaller of ($20\ \% R < D_2 \leq 40\ \% R$) or 60 m

– smaller of ($40\ \% R < D_3 \leq 60\ \% R$) or 90 m

– smaller of ($60\ \% R < D_4 \leq 80\ \% R$) or 120 m

– smaller of ($80\ \% R < D_5 \leq 100\ \% R$) or 150 m

where R is the maximum range of the 3D imaging system. A maximum of 150 m was selected as this was the size of many capital projects (e.g., process plants, construction sites, buildings, bridges).

Target Reflectivity (Refl.) - 5 levels:

– $0\ \% \leq$ Refl. $\leq 20\ \%$

– $20\ \% <$ Refl. $\leq 40\ \%$

– $40\ \% <$ Refl. $\leq 60\ \%$

– $60\ \% <$ Refl. $\leq 80\ \%$

– Refl. $> 90\ \%$

Angle of incidence (between the target and the line of sight from the instrument to the target) - 4 levels:

– 0º, 20º, 40º, 60º

Azimuth angle[1] (θ) - 4 levels:

– $0 \leq \theta \leq A/4$

– $A/4 < \theta \leq A/2$

– $A/2 < \theta \leq (3/4)\ A$

– $(3/4)\ A < \theta \leq A$

where A is the horizontal field of regard[2] of the 3D imaging system.

A total of 60 tests were suggested in the draft protocol (as opposed to 400 tests if every combination were to be tested).

The draft protocol proposes the use of a planar target that is a minimum of 0.5 m x 0.5 m in size. It also describes a method of processing the measurements to determine "valid" points. The calculated range to the target is then the distance from the instrument to the centroid of the valid points.

3. PROTOCOL EVALUATION

For the evaluation of the ranging protocol, a subset of the 60 tests was selected and two rounds of evaluation were conducted. The systems used in these evaluations would typically be used for industrial/manufacturing and construction type applications.

3.1 First Round of Tests

In the first round, a user performed a subset of the prescribed tests in a manufacturing facility with the participation of several members of the test methods subcommittee - ASTM E57.02.

Prior to the evaluation, target mounts and stands were fabricated and the stands were installed on the factory floor (see Figure 1). Thirteen of the 60 tests were performed.



Figure 1[3] Target and Target Stands

These were:

- AOI = 0º, target refl. = 20 %, θ = 0º
  - Distances: 7 m, 14 m, 28 m, 42 m, 70 m
- AOI = 0º, Distance = 28 m, θ= 0º

[1] The azimuth angle, as proposed in the ranging protocol, describes the angular range, within the instrument's horizontal field of regard (defined in Footnote 3), in which the target being measured lies

[2] The horizontal field of regard is the maximum angular extents (about the instrument's vertical axis - usually the Z axis) of an area of interest that can be measured by a 3-D imaging system as a result of scanning or reorienting the instrument's primary receiving axis

[3] Certain company products are identifiable in the photo. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose

- Reflectivity = 2 %, 20 %, 50 %, 75 %, 99 %

- Distance = 28 m, target refl. = 20 %, θ = 0º
  - AOI = 0º, 20º, 40º, 60º

The time to complete these 13 tests was approximately 8 h. with 4 people.

Some of the challenges encountered in performing the range protocol evaluation included:

- *Selecting a representative subset of the tests* - for example, instead of testing all target reflectivity values at all distances, test all reflectivity values at one distance. The question which then arose was which distance to choose: a distance closer to the instrument so that the effects of distance are minimized to reduce interaction between the two factors (distance and reflectivity) or a distance farther from the instrument to determine the "worst" condition? This leads back to the fundamental issue of the purpose of the test. Is the purpose to give the user an indication of how the instrument performs under various conditions or is it to determine if the instrument meets manufacturer specifications? Generally, more tests would be required in the former case than in the latter. In the latter case, only potential worst-case scenario tests would be specified
- *Determining the perpendicularity of the planar target with respect to the instrument*. Target perpendicularity was estimated by sampling 9 points on the target plane with a laser tracker. Since the 3D imaging system and the laser tracker did not have a common reference frame, the measurement was approximate, and was a cause for concern.
- *Determining ground truth measurements*. Since it was not possible to position the 3D imaging instrument over a known location point, the range protocol could only evaluate the relative range error.
- *Determining the sequence of tests to minimize set-up time*. For example, a laser tracker was used for ground truth measurements. The maximum range of the laser tracker was less than 72 m (the maximum test range). Therefore, the tracker had to be re-positioned for ground truth measurements at the longer distances. It was thus easier to complete all the tests at the shorter ranges first and then move the laser and complete all the tests at the longer distances.
- *Processing the data*. In particular, a transparent method for removing outliers and segmenting target points has to be agreed upon.
- *Targets*. The targets were cumbersome to work with as they were 0.6 m x 0.6 m, weighed about 11 kg, and had to be handled with care to avoid contaminating the target with oils and dirt. Mounting the targets on each platform was an additional cause for delay, which would likely be eliminated through the use of standard targets and mounts.

3.2 Second Round of Tests

3.2.1 Ranging protocol - planar targets

The second round of tests was conducted at NIST and a reduction in the number of tests was achieved through a 4^{4-2} fractional factorial experimental design (4 factors, 4 levels)[4] [2]. This experimental design reduced the number of tests from 60 to 16 and still enabled the estimation of the main factor effects. This design assumes there are no interactions between the main factors. The matrix of the 16 tests showing the various combinations is shown in Table 1.

The maximum range of the 3D imaging system used for these tests is greater than 100 m. However, since the maximum range achievable in the indoor space available was 100 m, the maximum range in these tests was set at 100 m. Again, since these initial tests were not meant to evaluate a particular instrument but rather the range protocol itself, this deviation from the protocol was considered acceptable.

The 3D imaging system used could be centered over a known location and this allowed evaluation of the absolute as well as relative distances.

A total station was used to measure ground truth - true distances. The total station and the 3D imaging system were placed at opposite ends of the 100 m test range with the target in between. An SMR (spherically mounted retroreflector) was

[4] This design is geometrically equivalent to the 4 x 4 Graeco-Latin Square

placed over a point on the floor and was set to the same height as the total station. The distance from the total station to the SMR was measured. The 3D imaging system was then placed over the same point, and the height to the center of instrument was set to that of the total station. An estimate of the uncertainty of the true distances is ± 4 mm based on variability of the target width, total station uncertainty, the ability to center the total station over a point, and determining which point on the target to use to get ground truth.

Table 1 Second Round, Planar Target Test Matrix

Test No.	Dist. (m)	Refl. (%)	AOI (º)	θ (º)
1	10	2	0	30
2	10	20	15	120
3	10	45	30	240
4	10	99	60	330
5	40	2	15	240
6	40	20	0	330
7	40	45	60	30
8	40	99	30	120
9	70	2	45	330
10	70	20	60	240
11	70	45	0	120
12	70	99	15	30
13	100	2	60	120
14	100	20	30	30
15	100	45	15	330
16	100	99	0	240

The general procedure was to move the target to the approximate location, level the target both horizontally and vertically and set the height of the center of the target to same height as the center of the 3D imaging system. The target was then visually set (see Figure 2) to an approximate AOI of 0º. The target stand had gradations from 0º to 360º and the initial value corresponding to 0º AOI was noted. The total station measured distances to the four retrotreflectors mounted on the back of the target. The target was then rotated to the required AOI and the target was scanned once.

To calculate the distance to the target, the points in the center of the target (approximately 25 % of the total target points per the protocol) were visually selected as the initial valid points (Figure 3). A plane was fit through these points and points with distances from the plane greater than one standard deviation were removed. The centroid of the remaining points was calculated, and the calculated range is the distance from the scanner to the centroid. (Currently, this process is performed manually but it can be automated.)



Figure 2 Target Adjustments

Preliminary results showing main factors effects are shown in Figure 4. The uncertainty of the measurements in Figure 4 is conservatively estimated as ± 5 mm. From these figures, the trends in the main factor effects are discernible. The total time to conduct the 16 tests with three people, including set-up, was about 7 h.

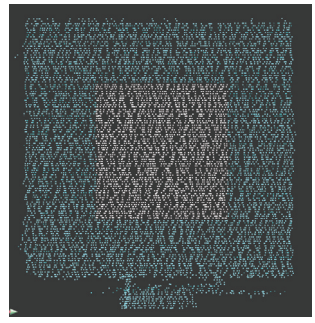
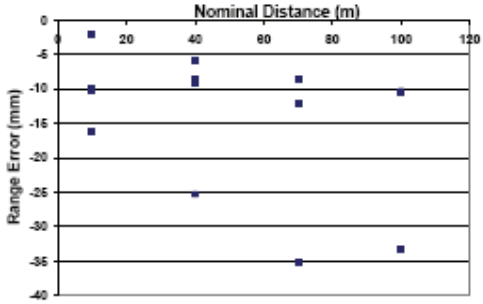
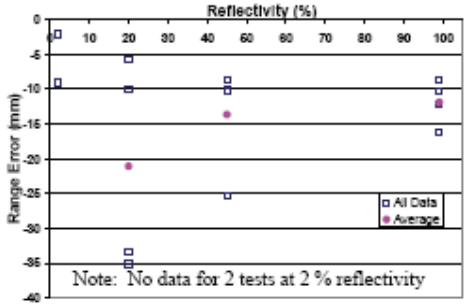


Figure 3 Selected Points in the Center of the Target Blue Points = Point Cloud of Target and Mount White Points = Selected Target Center Points.

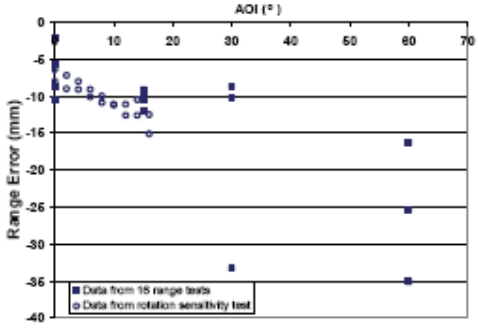
The process to isolate the target points and to select the points in the center was done in about 2 h. The time to process the total station data to determine the "true" distances took about 8 h. This included plane fits to determine the target plane, the normal to the target plane, and calculate the angle of incidence of the target plane.



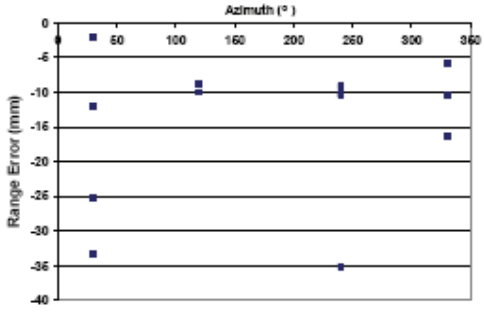
a. Effect of distance.



b. Effect of target reflectivity.



c. Effect of angle of incidence.



d. Effect of azimuth angle.

Figure 4 Main Factor Effects

3.2.1.1 Effect of selecting off center points

To determine the effect of using points that were not centered on the target, a short exercise was conducted. Points in the center, upper left, upper right, lower left, lower right quadrants of the target were selected. For each of these point sets, the previously described procedure to determine the centroids of these sets was used. The calculated ranges[5] from the scanner to these centroids are shown in Table 2. A comparison of the results for the four quadrants with the center value shows that the calculated ranges only varied by 1 mm to 2 mm - within the noise of these instruments. Obviously, the errors will be greater as the AOI increases.

Table 2 Effects of Selection of Target Points

Quadrants	Calculated Ranges (m) at AOI = 0º		
	1st Round of tests	2nd Round of tests	
	Nominal range = 28 m	Nominal range = 10 m	Nominal range = 100 m
Upper left	28.0050 ± 0.006	9.9707 ± 0.004	99.9829 ± 0.002
Lower left	28.0053 ± 0.006	9.9710 ± 0.004	99.9831 ± 0.002
Upper right	28.0062 ± 0.006	9.9716 ± 0.004	99.9863 ± 0.002
Lower right	28.0063 ± 0.006	9.9713 ± 0.004	99.9853 ± 0.002
Center	28.0058 ± 0.006	9.9707 ± 0.004	99.9842 ± 0.002

3.2.1.2 Effect of target rotation

When drafting the range protocol, there was a concern of how one ensures that the AOI between the target and the laser beam is indeed 0º - what if the target were not set exactly to 0º? How far from 0º can the target be rotated to have no significant effect on the measured range? Sensitivity tests were conducted to examine this effect.

For these tests, a 99 % reflective target was located at nominal distances of 10 m and 90 m from the 3D imaging system. The target was set-up in the manner described in Section 3.2.1 - starting with

[5] In this paper, the uncertainty of the measured distances is set equal to one standard deviation of the plane fit of the valid target points

an AOI of 0º. The target was scanned and then it was rotated in increments of 2º up to 16º. The Ground truth of the range from the target to the 3D imaging system as well as the AOI were measured with a total station. When the target was at an AOI of 6º, the rotation was visually discernible. results are shown in Table 3.

Table 3 Calculated Ranges of Rotated Target

AOI (º)	Calculated Range (m)		Range Error* (mm)	
	Nom. range = 10 m	Nom. range = 90 m	Nom. Range = 10 m**	Nom. Range = 90 m***
0	9.9847 ± 0.001	90.2839 ± 0.002	-6.4	-8.0
2	9.9839 ± 0.001	90.2829 ± 0.002	-7.2	-9.0
4	9.9835 ± 0.001	90.2826 ± 0.002	-8.0	-9.1
6	9.9814 ± 0.001	90.2826 ± 0.002	-10.1	-9.1
8	9.9815 ± 0.001	90.2808 ± 0.002	-10.0	-10.9
10	9.9803 ± 0.001	90.2806 ± 0.002	-11.2	-11.1
12	9.9793 ± 0.001	90.2804 ± 0.002	-12.6	-11.1
14	9.9793 ± 0.001	90.2810 ± 0.002	-12.6	-10.5
16	9.9769 ± 0.001	90.2789 ± 0.002	-15.1	-12.5

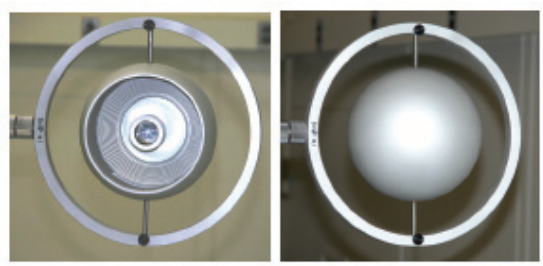
* Range Error = Calculated range - True range.
** Uncertainty = ± 4.1 mm
*** Uncertainty = ± 4.5 mm

Up to an AOI of 6º, the range errors varied by a maximum of 2 mm from an AOI of 0º. As noted previously, at a rotation of 6º, the fact that the plane of the target was not perpendicular to the propagation path of the laser beam was discernible and can be corrected.

3.2.2 Sphere Targets

ASTM E57.02 is also examining the use of spherical targets instead of planar targets. The use of spheres eliminates the need to level the target and to measure the AOI. Set up of the spheres is less cumbersome due to the reduced size as compared to the planar targets. The disadvantages of using spheres are that they are likely more expensive to fabricate, spheres with diameters of 300 mm or larger are needed at the longer distances, and a method of determining angle of incidence effects will have to be developed.

Only four of the 16 tests were conducted using spheres as only spheres with one reflectivity (spheres were anodized aluminum of unknown reflectivity - not critical for this protocol evaluation) were available and the AOI tests were not applicable. The four tests involved setting the spheres at four ranges at any azimuth angle and scanning them. The spheres used were not full spheres but rather 152 mm (6 in) diameter SMRs as shown in Figure 5. The general procedure was to center the sphere at the required nominal range and to set the height and horizontal position of the SMR so that its center was approximately along the line of sight between the total station and the 3D imaging system. A measurement from the total station to the SMR was made and then the sphere was scanned. The time to conduct the four tests was about 1.75 h. The time to clean the point cloud and perform sphere fits was about 2 h.



a. SMR side b. Sphere side

Figure 5 152 mm Diameter SMRs

4. FINDINGS AND FUTURE WORK

Some preliminary findings from the evaluation of the ranging protocol are:

- The reduction of tests from 60 as required in the draft ranging protocol to 16 appears to be a feasible alternative. These tests can be conducted in a day and the main factor effects can be evaluated.
- Methods of determining ground truth measurements need to be clearly defined in the protocol. The uncertainty of the true

- ranges were conservatively estimated as ± 4 mm using the total station in the second round of tests. This is about on the same order as some of the 3D imaging systems currently available. As the technology for these systems advance, it is anticipated that the range uncertainties for 3D imaging systems will reduce.
- Sphere targets were easier to use than planar targets. However, the disadvantages listed in Section 3.2.2 have to be considered.
- The effect on the calculated ranges is on the order of 2 mm for initial target rotations of 6º or less.
- The effect on the calculated ranges is on the order of 2 mm for the selection of points that are off center.

One of the assumptions for the experimental design used to reduce the number of tests from 60 to 16 was that there were no interactions between the main factors. Future work needs to be performed to determine if this is indeed the case.

5. ACKNOWLEDGMENTS

The authors would like to express their appreciation to the following individuals who were involved with the evaluation of the ranging protocol: David Ober of Metris, Michael Garvey and Jeff Cunningham of M-7 Technologies, Fred Persi and Darin Ingimarson of Quantapoint, and Pingbo Tang, PhD candidate at Carnegie Mellon University. The assistance of James Yen of NIST in developing the experimental design is also much appreciated.

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APPLICATION OF LOCATION INFORMATION BY STEREO CAMERA IMAGES TO PROJECT PROGRESS MONITORING

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ABSTRACT

In this paper, the authors discussed the overview of a method for estimating the 3-D coordinated data for development of a project control system with stereo camera images. The information for control project with location information in the 3-dimensional space of time series from images is proposed. SFM (Structure From Motion) is used for collection of camera motion and 3-D object data. The image collection on actual construction site was performed and 3D structure from stereo camera images was evaluated. According to the result, the possibility of the monitoring and the factors necessary to development for practical were proposed.

KEYWORDS

Location Information, Stereo Camera, Image Processing, Project Control

1. INTRODUCTION

In order to control progress of a project, it is necessary to check the information of resources placement in construction site such as workers, parts, and heavy equipments. However, while measurement and record of the location of resources depend heavily on physical observation of supervisors, the information of resources placement is difficult to be reflected in timely control of progress. In many cases, the actual location of resources which administrators cannot check are assumed based on operating reports from sub-contractors. Site management in the construction project becomes more efficient by monitoring and evaluating the location of resources.

In recent years, many studies have indicated that the automatic data collection is efficiency in construction management with development of the technology, such as GPS, RFID, LADAR, and image processing [1]. The authors have suggested the method to measure the location of workers using RFID [2]. The location information is placed as a main data for improvement of construction management.

Image processing by cameras has possibility as an alternative means of person's physical observation in the location-aware technology. Camera is one of the sensors which can collect much information economically. In the construction site, the advantages of camera images as a source of actual information have been recognized [3] [4]. However, in many cases, it is used for the watch of scenes at remote locations. One of the reasons for dependence on visual appreciation is thought to be the technical problem for automatic recognition in all environments.

The objective of this research is application of location information to project management and verification of data collecting process with stereo camera images. A prototype with commercial software was used for experiment, and the image collection is undertaken in actual construction site. Then the 3-D coordinates was calculated from the images, and determined the factors necessary for location information in control project.

2. APPLICATION OF 3D LOCATION INFORMATION IN PROJECT CONTROL

Installation progresses of construction are carried out on the site, and the each progress needs arrangement of resources such as workers, parts, and equipments according to actual condition for proper control of project. The workers are deployed in installation area to attach the stocked parts to the indicated place. The equipments are used in order to support handling, movement, remove, measurement, processing. Collecting of the time and position of resources in the level of task is required for the overall control of the project.

The real-time monitoring of location of each resource is useful to subjective judgment of experienced supervisors in process control. The estimation of condition of tasks and the formulation of problems using the location of resources are necessary. We can control the project progressively if we can collect how and where resources are performing. Also, it would be easier to make analysis for site management, such as safety, productivity and quality control.

Figure 1 shows control information on the tasks of each resource. In this paper, we defined the information as control information to control project. The control information is computed with location information in the 3-dimensional space of time series from images. For example, the installation interval from volume of parts, the moving distance of workers from 3-D coordinates, etc. are computed in time series.

A number of methods for collection of 3-D data of position in space have been developed. In this method, we examined the factors relating to the computation of control information and adopted stereo camera images. Although camera image processing has the technical problem for automatic recognition, it has the advantages that input data can be recognized visually and compiled heavily.

Many studies to reconstruct 3-D shape of the object from several images are contributed in the field of computer vision [5]. In this study, we used SFM (Structure From Motion) for collection of camera motion and 3-D object data. SFM estimates camera motions and reconstructs objects simultaneously based on epipolar geometry.

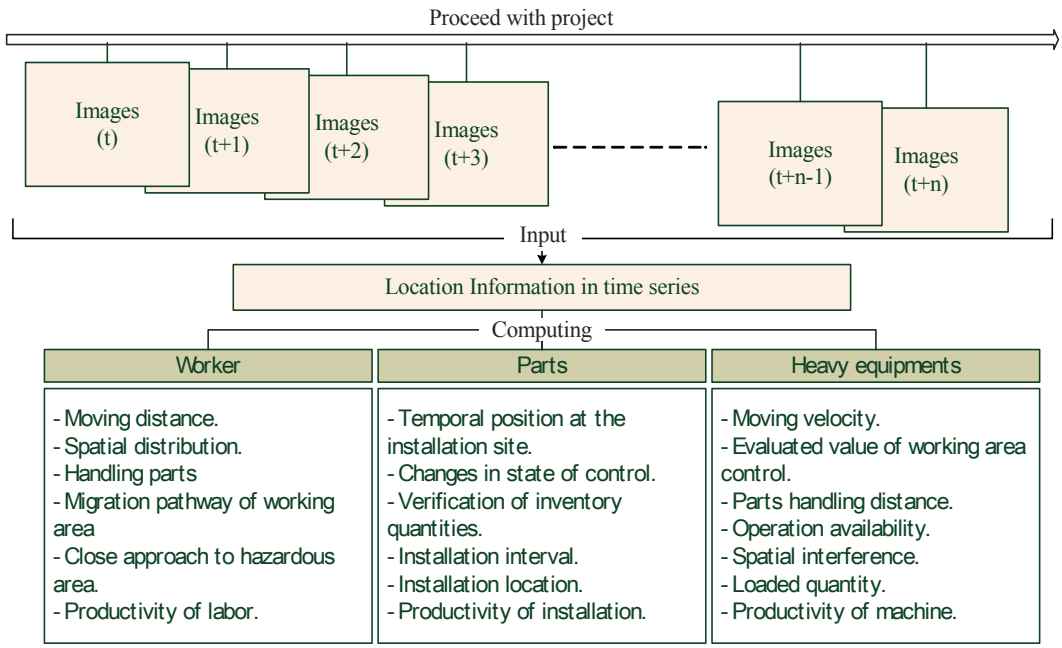


Figure 1 Computation of Control Information from Location Information

3. ACQUISITION OF 3D COORDINATE DATA WITH STEREO CAMERA IMAGES

3.1 Computing 3D Structure from Images

In order to reconstruct objects from more than one image, it is necessary to perform the camera calibration which is estimation of camera motions. The camera calibration can be classified two methods according to using coordinated makers. When using coordinated makers, the high accuracy of calculation is obtained, but the effort for installing is required. The effort of calibrations increases in the construction site with much change of the camera position for avoiding obstacles.

In this study, we performed the camera calibration with corresponding image points without coordinated makers and computed the 3-D coordinated data of objects.

Fundamental matrix F can be computed from pixel coordinates of correspondence points in no calibrated camera images [6]. The 8-points algorithm is a method of computing the fundamental matrix F [7].

If x and x` are corresponding image points, then the fundamental matrix F is unique (3, 3) rank 2 homogeneous matrix which satisfies Eq. (1). The fundamental matrix F is determined with more than 8 point correspondences (Figure2)

$$x'^{T} F x = 0 \qquad (1)$$

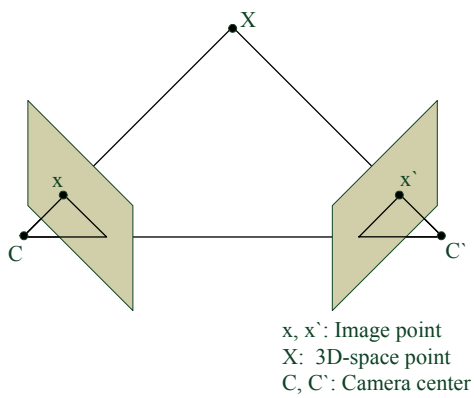


Figure 2 Point Correspondence Geometry

3.2 Experimental result

The authors performed the image collection on actual construction site in order to evaluate the 3D structure from stereo camera images. The images were obtained from installing underground structure and 3D coordinate data was computed with commercial software. The camera equipment used was HDV camcorder camera with digital video tape (Table1). We converted the digital video tape into AVI format suitable for computer image processing.

Table 1 Camera specifications

Product name	Sony HVR-A1J
Number of pixels	1440*1080
Aspect ratio(W:H)	16:9
Sensor type	1/3 inch CMOS

The two cameras were fixed on the tripods and installed on the roof of the neighbor building for film of the overall site. The installed height of camera is about 13 meters from first floor of construction site. Since the distance between two cameras influenced the calculation results, we set to about 10 meters as maximum allowable distance. The film was taken for one hour a day over five days. The posture and position of cameras was modified for everyday

Figure3 shows the results of camera calibration calculated with the corresponding image points of a day. We obtained 3D coordinate data of objects from calibrated camera images and computed the control information (Figure4)

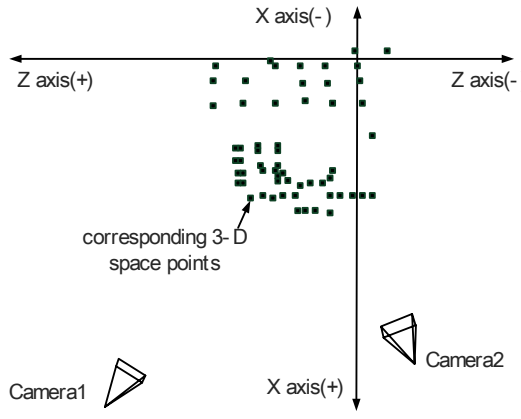


Figure 3 Results of camera calibration

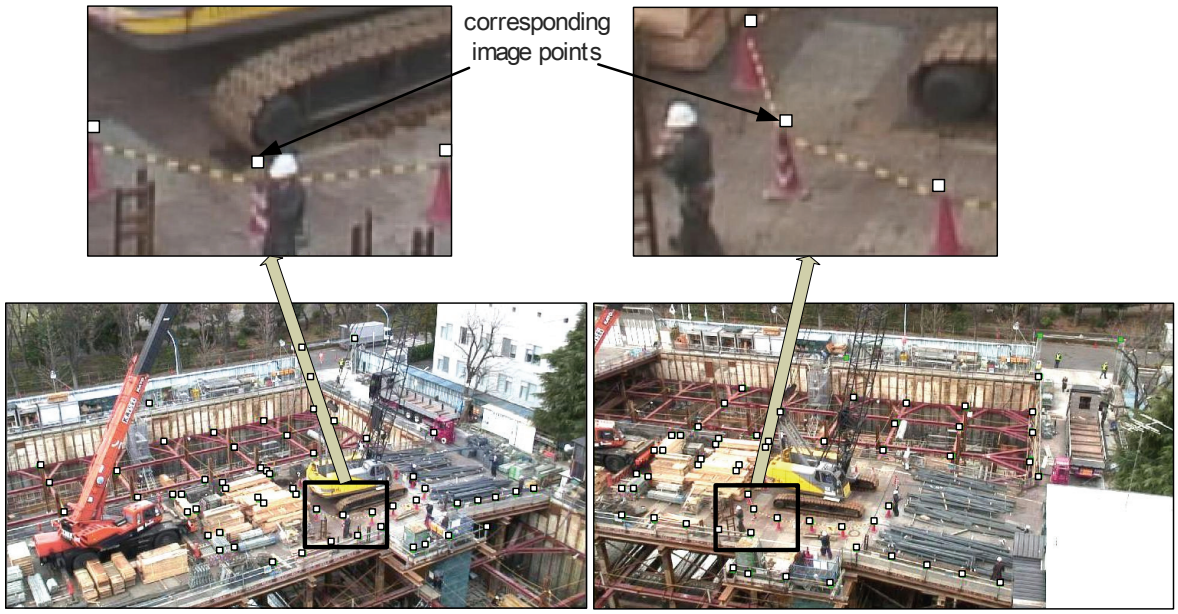


Figure 4 Images of Each Camera and Corresponding Image Points

4. CONCLUSION

The authors examined the application of the 3-D coordinate data by stereo camera images to project progress control. The experiment was performed and camera calibration results for calculate 3-D structure was obtained

After the research, we found that increases in position error due to camera characteristic. Relative posture of cameras, image resolution, and optical distortion may result measurement noise.

In order to apply reconstruct objects technology by camera images into the project progress control in construction site, stabilization algorithm on automatic recognition of objects, development of optical noise reduction process, and improvement of hardware performance are necessary.

5. ACKNOWLEDGMENT

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HYBRID METHODOLOGY FOR AUTOMATED COLLECTION OF DATA FROM CONSTRUCTION SITES

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ABSTRACT

Modeling 3D point cloud images scanned with the LADAR (LAser Distance And Ranging) is a time consuming process that lacks the capability of capturing material type, texture, and color of scanned objects. To extract information from construction sites and update quantities of work completed as well as mapping as-built information with the use of 3D scanners, many scans must be done from different positions and with high accuracy. Although some scanners are available in the market (e.g. the Z-series scanners from Riegl), which can scan a horizontal angel of 360º in a matter of 3 to 4 minutes, they are relatively expensive and photo images are still required to capture the attributes of material, texture and color referred to above. On the other hand, modeling 3D images using photo images alone has its drawbacks such as, for example, the difficulty of locating excavation edges. This paper introduces a method that integrates both technologies (i.e. LADAR scanning and Phtogrammetry) to collect data from construction sites pertinent to quantities of work accomplished, used subsequently for progress reporting.

KEYWORDS

3D Laser Scanning, Photogrammetry, Progress Reporting, Data Acquisition, Automation

1. INTRODUCTION

Integrating 3D scanned images with digital photo images to enhance the 3D modeling process allows the overcome of limitations associated with both technologies. One of these major limitations is the time required to scan the construction from different positions to get enough information needed for the modeling process. This method saves time related to the number of scans needed and also enables the use of scanners with low accuracy, which saves cost and make it feasible to the construction industry. The proposed method utilizes (1) a commercially available modeling software (PHIDIAS), which models both 3D point cloud images and photo images. (2) 3D scanner (LPM 100 VHS LADAR), (3) the software RiProfile, installed on a tablet PC (Fujitsu - Stylistic ST4121B) to generate 3D "point clouds" from different positions and (4) a Digital camera (Olympus C750). The process starts by scanning an object from different positions and capturing digital photo images of that object, not necessarily from the same scanning position. The resulting point cloud images and digital photo images are then merged using the software PHIDIAS to enhance the quality and accuracy of the geometric characteristics of the scanned objects, which in its processed digital form is used to estimate the quantities of work completed. The proposed method is used to report cumulative progress and period-by-period progress report. The paper also will present the finding of the application of the

proposed method on an actual currently under construction project in the Montreal area. Advantages and limitations of the 3D scanning and Photogrammetry are highlighted.

2. LADAR

LADAR scanning is the process collecting 3D points or "point clouds" that are later processed using software packages, to transform these points into 3-D objects to be used subsequently in calculating quantities of work completed on site. The data points are given in *x, y, z,* coordinates. The LADAR technology works by sending illumination pulse to an object and receiving it back. The distance between the object and the LADAR station is called the "Range". The laser beam traverses a distance equal to 2d [1]. The time needed to accomplish this operation can be expressed by Equation 1 below.

$$T = 2\mathbf{d}/c \qquad (1)$$

Where "c" is the speed of light, "d" is known as the "Range" and is defined as the distance between the object and the LADAR, and "T" is the travel time. It was reported that a clock time of 1ns (nano second) represents a 300 mm round-trip or an absolute range "d" of 150 mm (Stone *et al*. 2002). Every pulse will produce a pixel or a point in a point cloud that represent a range image. At the early stages of the current research some test scans were performed to identify the scanner accuracy. The modeling software package POLYWORKS was used to process scanned images [2], [3]. The scanning activities were performed with the Riegl LPM 100 VHS LADAR scanner. Figure 1 illustrates the scanner while connected to the tablet PC (Fujitsu - Stylistic ST4121B) via a serial cable during the scanning process. After creating a new project on RiProfile, the rage angels must be set with the help of the scanner configuration window (Figure 2).

The horizontal and vertical range angles are set to identify the image need to be scanned. The resolution of the scan can be affected by the resolution angle. This angle together with the distance from the object to the scanner specifies the distance between each point in space. The angle is also known as the angle of incidence [1].



Figure 1 Site Scanning

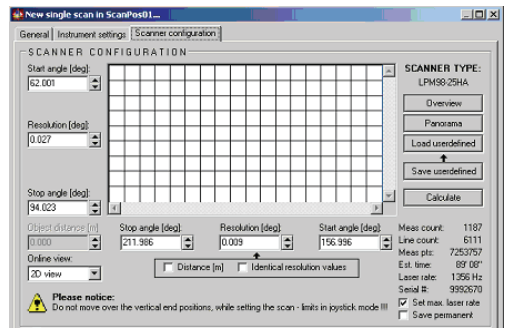


Figure 2 Scanner Configuration

3. SITE SCAN

The new building of Concordia for the business department was considered for test scans. The construction site is 60 m x 40 m and scans were performed along the longer side. The purpose of the scan is to model scanned images and estimate quantities of work performed at the end of working day. The time of a single scan depends on the vertical and horizontal resolution angles and for a construction site of that size it was necessary to scan it with a wide horizontal angle of about 200° and vertical range angle of 59°. The vertical and horizontal resolutions were set then equal to 0.2°. The time required to scan this range were found to be about 26' 36" and the number of points in the point cloud image were 295,295. The second factor that affects the resolution next to the resolution angle is the distance of the scanner to the scanned object and as the site was scanned form its long side, that distance varied from 1 m to about 50 with an average of 30 m. If we consider the 30 m then the distance between two adjacent

points of the point cloud image with a resolution angle of 0.2° would be about 10cm. This of course is considered low accurate and if the resolution angle have to be decreased to give a distance of about 5 mm between the points then it must be 0.01°. The horizontal resolution angle was set to 0.01° while the scanner automatically set the vertical to 0.027°. The result of these configurations was as follows. Time required for scanning the same horizontal and vertical range angle but with enhanced resolution angle approached the 50 hours with a number of points in the point cloud image of 42,690,956. Knowing that scans must be at the end of working day and few scans must be performed it was impossible to set the scanner configurations to such data. Despite the fact that there exist scanners, which can take much faster time to scan the same image like the Z-series from Riegel [3] it was clear that even after scanning with higher resolution the scanned image will lack information pertinent to texture and color of the scanned object and additionally, many scans can not be avoided to get enough information and consequently, a photo image must be available to help in 3D modeling of the scanned image. Another observation were found when working with the LPM 100 VHS LADAR is when decreasing the resolution angle the point cloud image would be very congested and not on the same level.

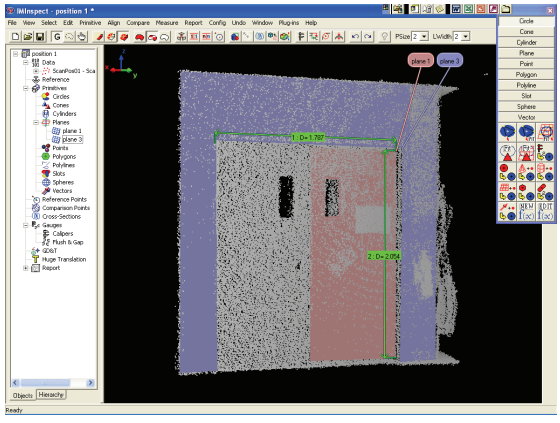


Figure 3 Front View of Scanned Lab Door

Figure 3 is the result of a scanned door lab with a horizontal resolution angle of 0.015° and Figure 4 depicts the horizontal cross section of that door. As shown in that figure, the points are not on the same plane, which makes it difficult to get the door dimensions.

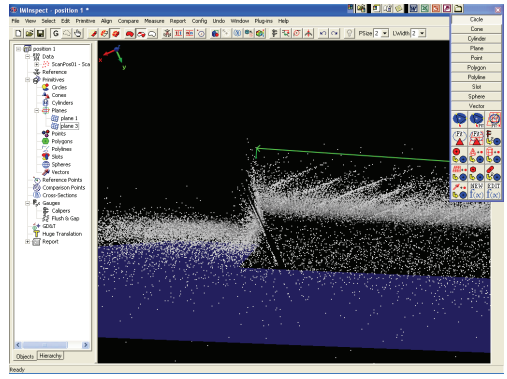


Figure 4 Horizontal Cross Section in the Lab Door

4. 3D SCANNING AND DIGITAL PHOTO IMAGES

The main limitation lies with the LADAR is the time required to scan an object from different positions to get enough information regarding its geometrical properties. To overcome this limitation the authors thought of integrating digital photo images with the scanned image. Digital images provide detailed information pertinent to object color and texture. It remains time consuming to model 3D images from only digital images. The reason for that is the time required to position many targets with known coordinates that assists in the modeling process.



Figure 5 Targets Placement for 3D Modeling from Photo Images

As illustrated in Figure 5, targets must be placed in the image to be able to identify the coordinates of the different objects in the image. The process of

taking images together during the scanning process works by installing a digital camera on top of the scanner and after calibrating the camera still images are taken automatically during the scanning process. The disadvantage of this method is that images are taken from the same distance and the same angle as the scanner because it's mounted on the top of the scanner. As the scanner used cannot be mounted with a digital camera, this brought the authors to the idea of taking images with a separate camera and connects the images later during the modeling process with the scanned images. This enabled taking images from different angles than the scanner position and also in a different distance, namely closer distance, than the scanner distance to the object, which provide more information on the scanned object and minimizes the number of scans required. A scan was performed on the same construction site of Concordia University. The scanner configurations were as follows: Horizontal range angle is 165 ° and vertical is 55°. The horizontal and vertical resolution angles are equal and they are 0.2°. These configurations resulted in a total number of points in a point cloud image of 227,976 and scanning time of 20'45". The scanned image is then exported to modeling software PHIDIAS and is shown in Figure 6. Digital photo images were taken from different angles to be used as supportive tools during the 3D molding process.

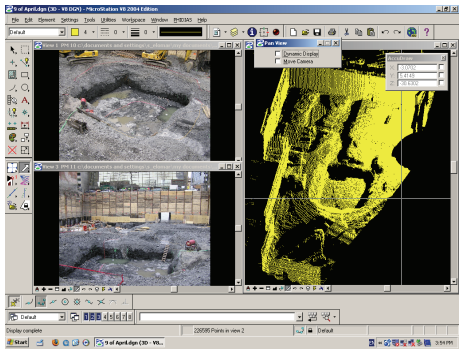


Figure 6 Scanned and Digital Images

As shown in Figure 7, due to the scanner position some areas were not scanned because they were hidden and represented with black are shaded spots. The use of a digital camera enabled to get information on these shaded spots. After importing the scanned image from RiProfile to PHIDIAS and loading the photo images they must be oriented to link them together. The orientation process is done with the tool available in Phidais software called "Special Resection".

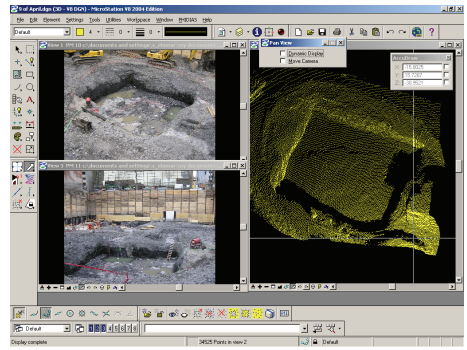


Figure 7 3D Modeling with Scanned and Digital Images

Through this process common points are selected and joint together in the point cloud image and the digital photo image (Figure 8). Another way of connecting the images together is by knowing the 3D coordinates of the same points. This is important in the case of modeling 3D images for as-built information purposes. As we mentioned before the purposes for modeling is to estimate the quantities of work performed and therefore finding common point in the scanned and digital image would be sufficient for that purpose. The result of that is shown in Figure 9 and Figure 10. As noticed the problem if having a distance between the points in the point cloud image up to 10 cm because of the large resolution angle is now solved

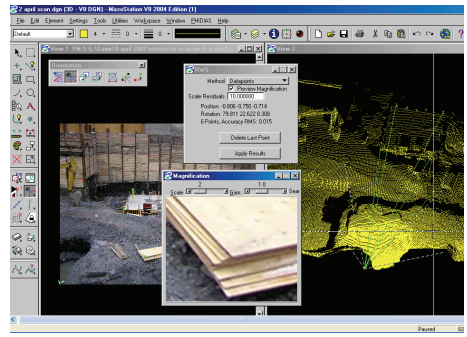


Figure 8 Connecting Point Cloud with Digital Images

and the dimensions can be now more accurately extracted with only one scan and few digital images.

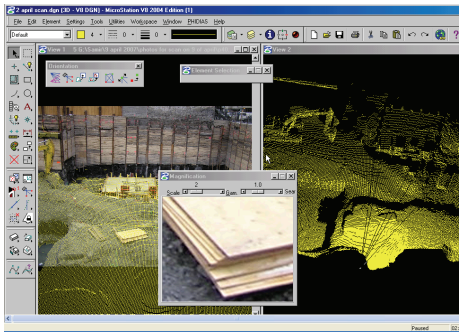


Figure 9 3D Modeling

The construction site is scanned at different times to generate data, which can be used to estimate the quantity of work accomplished within the time interval considered between two successive scans.

5. CONCLUSION

Automating the process of data collection to estimate quantities of work performed on construction site is a method to enhance the progress reporting activity in a timely and accurate manner. Researchers have applied 3D laser scanning as a tool collect data from construction sites [4], [5] and [6]. Traditionally quantities are either estimated through the manual measurement from construction site, which is time consuming, or extracting the quantities from design drawings and this can be inaccurate due to changes that might occur on construction sites. 3D Modeling can be time consuming if it only relies on scanned images because many scans have to be conducted to get enough information for the modeling process. Incorporating digital images can reduce the time required during the scanning process and allows scanning with higher resolution angle. Scanned and digital images are modeled together and quantities of work performed are estimated. The proposed methodology is part of an undergoing research that integrates different data acquisition technologies to automate the process of data collection from construction sites, compare it to planned ones, and subsequently generate progress reports.

6. ACKNOWLEDGMENT

The authors would like to thank the Riegl Company for the training and continues technical support they provided to the first author.

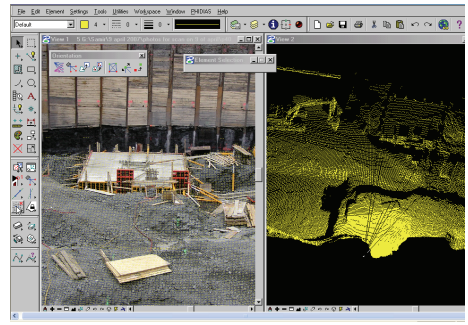


Figure 10 3D Modeling

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SAFE AND EFFICIENT AUTONOMOUS EXPLORATION TECHNIQUE FOR 3D MAPPING OF A COMPLEX BRIDGE MAINTENANCE ENVIRONMENT

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ABSTRACT

This paper describes a technique for autonomously exploring a complex steel bridge environment using a 6DOF anthropomorphic robotic arm, instrumented with a laser range scanner. Potential knowledge gained from a 3D range scan at an end-effector position and orientation (pose) is estimated, then arm configurations which avoid obstacles and unknown areas are computed using an optimisation approach. Safe pose solutions are compared in terms of potential gain of new weighted-information and minimal joint movement. Both simulations and robotic platform results show exploration of unknown areas occurs in a consistent and timely manner - taking an average of 4.5secs to calculate the next safe valid robot arm poses. Complex environments, typical in bridge maintenance, can be explored using an anthropomorphic arm equipped with this technique.

KEYWORDS

Exploration, Collision Avoidance, Bridge Maintenance, Inverse Kinematics

1. INTRODUCTION

The removal of paint and rust via sandblasting, followed by the reapplication of a protective coating is an essential part of bridge maintenance: the process significantly reduces the likelihood of structurally damaging rust. However, due to newly introduced OH&S regulations, it is no longer desirable for humans to perform this task. Problems arise from commonly used lead based paints and the likelihood of working in close proximity with asbestos. Thus there is little alternative other than performing a significant portion of this bridge maintenance work with a robotic system.

In order to place a robotic system in a complex environment typical of that in bridge maintenance, the system requires a method to rapidly obtain detailed on-demand surface maps [1] to facilitate robot-environment interaction. Alternate mapping solutions are not feasible: up-to-date maps are not available; manual generation of maps is prohibitively time consuming; and teleoperated based mapping/ exploration presents a high risk of collisions. As the risk of robot-environment collision is high [2], there is a need for an intelligent and efficient technique able to 'safely explore' the workspace of the robot arm and sandblasting/painting range.

Prior research into mechanised bridge maintenance where paint is removed from steel bridges by means of a teleoperated arm [3] did not address the situation where the environment is enclosed - access was gained from a truck on the bridge. The focus of this work was on teleoperation rather than autonomous blasting [2] hence exploration was not required. Algorithms for obstacle detection and avoidance during path planning, as well as robot collision-free exploration techniques in 2D [4,5] where sensors are mounted on the mobile unit, are ineffective at solving 3D issues. Wolf et al. [6] developed a mobile unit for autonomously exploring terrain but this work focussed on localisation rather than mapping for surface interaction.

Coverage and next best view algorithms for robot arms are active research areas but these algorithms generally do not consider potential collisions in unexplored space. Several sensor Next Best View (NBV) algorithms [7,8] were identified as possibly applicable however additional constraints on movement are also required. Additionally, NBV algorithms for object reconstruction in computer aided manufacturing/bypass-engineering generally assumed the workspace in which the sensor is moved is safe. Another example of exploration is the stair-climbing robot [9] however simplifications to 2.5D make it not suitable for this application. Ultimately, next view deterministic approaches do not specifically address the problem of predicting new weighted information while considering anthropomorphic arm based exploration which avoids possible collisions with both known obstacles and unknown obstacles in unexplored areas.

Inverse kinematics solutions which find suitable joint configurations are an essential part of an exploration technique for an anthropomorphic arm [10]. Importantly, different joint configurations can result in the same end-effector transform (Fig.3) hence increasing the probability of manipulator collisions - inverse kinematic approaches commonly experience local minima problems. An optimisation approach based upon [11,12], if adapted by adding optimisation constraints and using various starting points - to avoid local minima - would provide a viable solution. Sujan [11] developed an innovative exploration technique but it uses stereo vision for mapping. Overall, a set of integrated solutions are required for 6DOF manipulator exploration without prior information including: mapping, exploration, collision avoidance and inverse kinematics.

This paper presents a technique for safe efficient 3D data collection for 3D mapping an initially unknown environment (Fig.1). The technique ensures collisions between the robotic arm and obstacles or unknown space are avoided and that the robot proactively seeks poses which will deliver maximum new data that require minimum movement to get to. Results have shown that this technique is a viable solution to our exploration problem as maps for bridge maintenance are safely acquired in a timely manner.

The breakdown of this paper is as follows: section 2 introduces the proposed exploration technique, describes how information gain is determined, how poses are selected and how movements that avoid collision are determined; and section 3 presents results from experiments conducted in a structured bridge environment.



Figure 1 Left - Bridge Sandblasting Environment Right - I-beam Channel Scale Model: First Scan from Unobtrusive Position

2. EXPLORATION TECHNIQUE

The technique commences with the robot arm in its most unobtrusive pose; assumes completely unknown surrounds; and performs an initial scan with the fifth joint so as not to enter unexplored areas (Fig.1 *right*). Then, through the range, tilt and pan considerations of the laser range scanner instrument, the amount of weighted information (Fig.2) gained from a number of possible 3D scans is calculated. Different areas are multiplied by weighting coefficients (equation (1)) depending upon our desire to explore them - the workspace of the robot arm is of most importance. As can be seen in Fig.3 the end-effector can be in the same physical location with the robot in various configurations, however some configurations may cause part of the robot to enter unknown space and thus introduce the possibility for collision. The technique will then drive the robot, with assistance from a local path planner between poses [13], to a physical location that will give the system the largest amount of desired information while avoiding obstacles or unexplored space.

$$\Delta Info = C_1 \times A_1 + C_2 \times A_2 + C_3 \times A_3 \qquad (1)$$

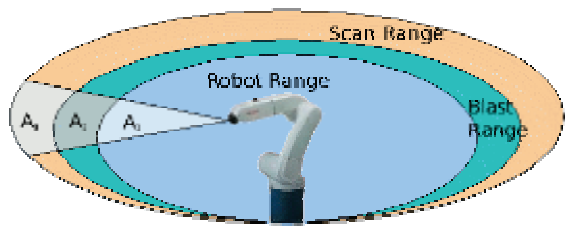


Figure 2 Areas of Importance $\{A_1\ A_2\ A_3\}$ Weighted by Constants During Exploration

The technique employs a spatial index to classify the surrounding space into known free space, known obstacles and unknown space. When range data is recognised as a surface, the data is minimised by storing bound surfaces and normals [1]. Obstacles represented by surfaces created from range data are considered, as is the pose and dimensions of the robot arm, so as to avoid issuing commands to explore from areas that endanger the robot arm.



Figure 3 Joint Configurations Resulting in Same End-Effector Transform

The integrated steps of this technique (Fig.4) can be separated into: predicting information gain from different poses by considering the laser model, tilting limitations and obstacles' obscuring effect; determine joint configurations for desired end-effector poses; minimise probability of arm collisions by avoiding obstacles and unknown areas. These components are used to maximise weighted new information gained while minimising joint movement when selecting the next increment of exploration.

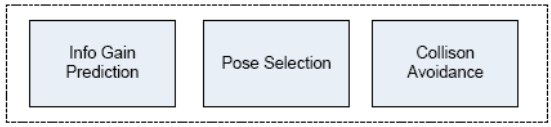


Figure 4 Processes Incorporated into Technique

2.1 Information Gain Prediction

Possible scan positions are chosen from a discretely sampled set of points in the robot arm's currently known workspace. In order to accurately predict 3D information gain a laser model was developed for the sensor constraints and capabilities: the 2D scanner field of view (max. pan angle); resolution; maximum tilt angle (5^{th} joint); range; and accuracy.

The aim of this prediction step is to maximise new information (weighted by area's importance Fig.2) at each increment of exploration. As the angle of the tilt scan (5^{th} joint) increases so does the: time taken; the number of points in space; and the amount of data which needs to be processed. Fig.5 shows a wireframe enclosed area to the right (blue) predicted to be found from a scan (note: in this figure the pan angle is not maximised). Where previous exploration revealed obstacles, bound plans are created using [1]. It is then possible to exclude information obscured by the obstacle to the left (red), from new information predictions. As the tilt or pan angles increase the expected area of new information increases. However, as the 5^{th} joint is also used to manoeuvre the 6DOF manipulator, it is desirable to constrain the movement during pose selection so as to maximise tilt angles. This is included in the objective function of the pose selection optimisation.

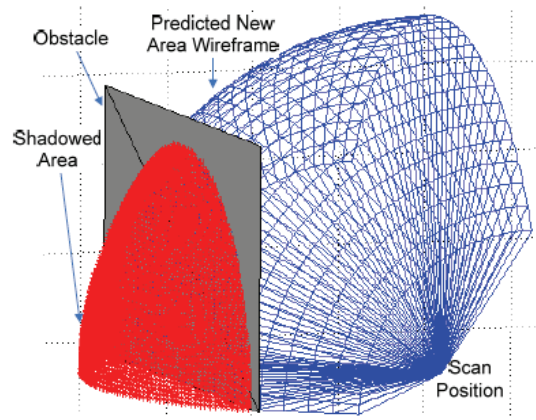


Figure 5 Visualisation of Predicted Scan Area

2.2 Robot Pose Selection

In the case of a simple actuator - 1 or 2 DOF, the poses for different objectives are easily determined. However in the case of a 6DOF anthropomorphic arm it is a more difficult due to local minima, joint constraints and multiple possible solutions, some with a high probability of collisions.

As the calculation of the inverse kinematic solution is relatively time consuming, rather than calculating joint configurations over a discretely sampled 3D space, we choose to calculate several possible desirable viewpoints in which to place the sensor based upon new scan information predictions, then determine poses for these. In this case the input is the transform which will position the end-

effector (and sensor) in free space with an orientation of $\{\vec{a},\vec{b},\vec{c}\}$ where $\vec{c}$ represents a vector at the centre laser scan ray. Then possible joint configurations are calculated for this transform. The inverse kinematics determination requires efficiency since multiple possibilities are calculated and checked for collisions online.

An inverse kinematics optimisation approach, modified from [11,12], has been reworked to suit this application. The exploration technique passes a number of possible starting joint configuration positions (so that the inverse kinematic optimisation approach has a greater probability of avoiding local minima). Iterations and termination conditions of the optimisation are also tuned for efficiency. Termination occurs when the cost function gradient is no longer improving.

Joint limitations are also considered and poses which are outside of these limits are discarded. Equation (2) is the optimisation algorithm's error vector used to find joint configurations. It includes the distance away from the desired pose and the difference in orientation. Where P_d=$\{x_d,y_d,z_d\}$ is the desired end-effector position and $\{\vec{a}_d,\vec{b}_d,\vec{c}_d\}$ are the desired orientation vectors of the end-effector. The current transform of the end-effector is at position P_c=$\{x_c,y_c,z_c\}$ with orientation $\{\vec{a}_c,\vec{b}_c,\vec{c}_c\}$.

$$\vec{E}=\begin{bmatrix}\left[\vec{a},\vec{b},\vec{c}\right]^T\bullet\left[\vec{P}_c-\vec{P}_d\right]\\ e^{k_1\left(\sqrt{(t_d-t_c)^2+(t_d-t_c)^2+(t_d-t_c)^2}-C_T\right)}\\ e^{k_2\left(\sqrt{(x_d-x_c)^2+(y_d-y_c)^2+(z_d-z_c)^2}-C_A\right)}\\ e^{\frac{|q_5|-C_D}{5}}\end{bmatrix}\quad(2)$$

The constraint constants are as follows: C_T is the maximum acceptable distance from the desired target; C_A is the maximum allowable distance from the desired target and the actual target; C_D is the maximum angle allowable off the desired orientation of the end-effector which dampens the movement of the 5th Joint (q_5). Since joint 5 is used to tilt the 2D sensor through a 3D scan, it is important that its range of movement is not over-utilised while reaching the desired pose. In the error vector, values greater than the constants cause the error vector to become exponentially large. Overall the cost function is minimised as the actual end-effector transform gets closer to what is desired. This results in a quick (milliseconds) method to determine constrained inverse kinematic solutions.

2.3 Collision Avoidance

As shown in Fig.3 different joint configurations calculated from the pose selection step can result in the same end-effector transform. Therefore a collision avoidance technique closely associated with pose selection is required. Using a force field method based upon [2], all joints are encased in virtual force fields as shown in Fig.6 (only shows encasing around joints 3-6).

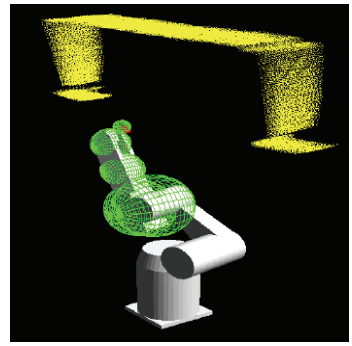


Figure 6 Virtual Force Fields Around Joints

In this case the force fields around the joints are defined at the initial configuration stage and set to *JointFF* for joints n=1→6. Collision avoidance checks involve performing forward kinematics on the 6DOF robot arm model using the determined joint configurations, then calculate the distance from the link *n* center $\{x_n,y_n,z_n\}$ to the points within the robot range $\{X,Y,Z\}$ of both unknown space and obstacles.

$$\forall n\in\{1\rightarrow 6\}$$
$$if\left(\sqrt{(x_c-X)^2+(y_c-Y)^2+(z_c-Z)^2}\le Joint FF_n\right)$$

if the above algorithm check returns true, then a collision is possible – since one of these joint virtual force fields has unknown points/known obstacles within its defined force fields. Otherwise this is an acceptable solution. Acceptable solutions are weighted then compared so as to determine the next exploration step which has maximum predicted information gain and minimal required joint movement.

3 RESULTS

Initial implementation focused on the development of a simulation (Figure 7) to check the validity of the developed technique complement experiments. This allowed for the viewing of the explored area (Figure 7 *left*), an essential part of collision avoidance and information gain predictions. It displays obstacles, movement of the robotic arm within the environment and information predictions.

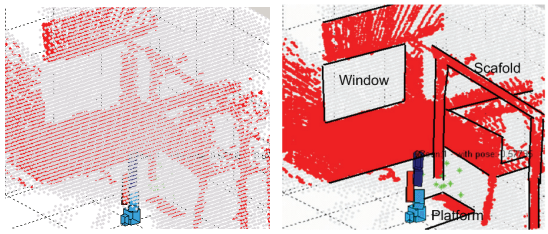
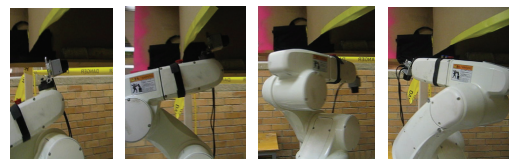


Figure 7 Environment/Robot Simulation Program
Left - Grey Points Showing Known Free Space
Right - Objects Edge Highlighted, Objects Labeled

One reason for automation as opposed to teleoperation is due to human's difficult interpreting freespace (Fig.7 *left* in grey to highlight). Although inadequate for human participation, these points provide the system with an invaluable understanding about possible positions for the 6DOF manipulator. Fig.7 *right* highlights the edges of different objects - the window and scaffold are clear from the 3D obstacle model produced with minimal exploration.

To evaluate the technique, robotic platform experiments were setup on a scale model of the intended environment (Fig.1 *right*). Several experiments were designed to show the technique's ability to identify real physical space that could potentially yield the highest amount of valuable information whilst positioning the robot arm only in collision-free configurations. Fig.8 shows the image sequence of one experiment. In this case, the robot was positioned with an obstacle (girder) in close proximity and directly above it a) and a scan was taken and environmental information gathered by the exploration technique. The position seen in b) was selected as the next best position to scan from. This result highlights the ability to consider the required physical movement of the robot as well as the potential for information gain when deciding the next position. Although intuitively, seemingly more information would be gained from scanning on the other side of the vertical partition, it is determined that the highly-weighted close proximity information remaining to be gathered on this side of the vertical partition teamed with the expense of the large robot movement makes the scan shown in b) the most efficient, yet valuable, next scan. After b) the technique moves the robot to a position on the other side of the vertical partition, shown in d), as little information remains available on this side of the partition. As can be seen in c) and d) the robot swivelled underneath the vertical partition avoiding collisions.



a) b) c) d)

Figure 8 Image Sequence of Exploration

This result clearly shows the technique's ability to select the next best view based on the amount of information available at that new position and the required movement to get to that position whilst ensuring collision avoidance.

Preliminary comparative testing found that it is extremely difficult for a remote human operator to determine possible safe configurations for the anthropomorphic robotic arm due to the difficulty in differentiating between known or unknown space. Additionally it is difficult for humans to estimate potential information gain when there are obstacles in the environment and the scanner tilt/pan angles are greater than 90°. Conversely preliminary results saw the technique presented here was quick (averaging 4.5sec) and reliable (0 obstacle collisions) at calculating potential information from safe joint configurations, resulting in successful exploration.

4. CONCLUSION

The technique's ability to successfully consider and collect the data required to construct a weighted interest-area map in a time and physical movement efficient manner without the risk of collision has been experimentally verified and demonstrated. This method has been shown to be a valid solution to the critical problem of how to safely and

efficiently collect the required data to construct an environmental map of the bridge maintenance environment. Future work will focus on continued efficiency improvement of this technique and extensive comparative testing.

5. ACKNOWLEDGMENT

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INSPECTING INTERIOR BUILT ENVIRONMENTS USING AUGMENTED REALITY-BASED AUTONOMOUS ROBOT

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ABSTRACT

During the past several years, there has been an increasing interest in deploying mobile robots to inspect building structures. Augmented Reality (AR), which can impose digital information into the real working space, has been proved to be effective in providing most relevant information in an intuitive manner. Combining the strength of these two technologies, this paper proposed an Augmented Reality-based autonomous robotic inspection system for interior built environments. A novel path-planning optimization algorithm was also developed to improve the success of the main goal of the robot using specialized sensors when available. The algorithm can also avoid obstacles and cycles in the search, and handling errors. Experimentation on the effectiveness of this algorithm and system was conducted and the preliminary results are discussed in this paper.

KEYWORDS

Augmented Reality, Autonomous Robot, Built Environment, Inspection

1. INTRODUCTION

There has been an increasing interest in deploying robots in built environments. For example, robots have been developed to level and compact concrete [1], to set tiles [6], to finish interiors [14][15], and to detect concrete cracks [16]. Robots have also been applied as an efficient solution to explore inaccessible environments in the areas of underground sewer pipe inspection [11], removal of damages being result of disasters [2], remote assembly of planetary structures [3], etc. To this end there has been much research on how to effectively operate remote machine (e.g., navigate into an area, perform actions such as taking samples, navigating, performing manipulation, etc.). Although many robots have been developed over the past decade, very few have been used for daily operation and maintenance of existing buildings [13]. It is envisaged that autonomous robots can be employed to handle routine building operations. Such autonomous robots should be designed to move around the building without much human/objects interference. Robots should have the capacity to retrieve real-time images which are then sent back to the management centre. The key behind such robots is accurate self-identification of its own position and selection of the optimal path to maneuver around the building freely [4][9][12].

Augmented Reality (AR), which appears in the literature usually in conjunction with the term Virtual Reality (VR), is a technology or an environment where the additional information generated by a computer is inserted into the user's view of real world scene [8]. AR can create an augmented workspace by inserting the virtual space in which we store and interact with digital contents into the physical space where people work. In the area of built environment, remote control of working robots operation is necessary when there is no physical possibility for a man to be in a machine or in its neighborhood.

Augmented Reality has been investigated to be combined with robots in executing certain tasks. For instance, a setup for a mobile user employing Augmented Reality for indoor and outdoor applications has been developed at Delft University of Technology [5]. To determine the user's position and orientation in the world, it used a cognition system similar to that used by their autonomous soccer playing robots.

This paper proposed an Augmented Reality (AR)-based autonomous robotic inspection system for interior environments. The focus of the paper is the development of a novel path-planning optimization algorithm to improve the success of the main goal of the robot using specialized sensors when available. The rest of this paper is organized as follows. Section 2 presents the system architecture including hardware, software, and functionalities. Section 3 presents the proposed path-planning optimization algorithm. In Section 4, the preliminary experimental results are discussed.

2. SYSTEM ARCHITECTURE OF THE AR-INTEGRATED ROBOT

The primary goal of the system is to find a place in built environment within a minimum possible time interval. The secondary goals are avoiding obstacles, searching the area effectively, avoiding cycles in the search, turning and moving to the directions of locations in which it is believed that points of interests are located. There may be static or dynamic obstacles, other robots, and the human in the built environment. The environment structure and the map are unknown.

The mobile robot is equipped with sensing camera which collects data to reconstruct the visual image of built environment and the operator workstation has a laser scanner to locate the accurate positions of the robot. The goal of the robot is to obtain a perception of the environment from the observed scenery and to provide a map of its workspace.

The system consists of three core modules: sensing, mapping, and guiding as shown in Figure 1.

2.1 Sensing Module

The sensing module interfaces directly with actuators and sensors of the robot and is responsible for avoiding obstacles, controlling velocity, and transiting sensed information through wireless network back to the operator workstation.

2.2 Mapping Module

The mapping module retrieves sensed information from the real scene and then re-constructs a live interactive 3D virtual rendering of the robot and the environment by mapping the sensed visual image data and the robot position to a 3D world created by OpenGL. This layer also constructs the plan for the robot to implement its task in an optimal way. The strategies for avoiding cycles, forming beliefs to direct the search space, and exception handling are implemented by this layer.

2.3 Guiding Module

The guiding module uses Augmented Reality technology to overlay the virtual directions (strategies made in Augmented Reality) onto the robot's camera's real view (operator's remote view) to control the robot's navigation. The system also uses AR technology to annotate the virtual dimensions/directions onto the camera's real view (operator's remote view) to control the robot.

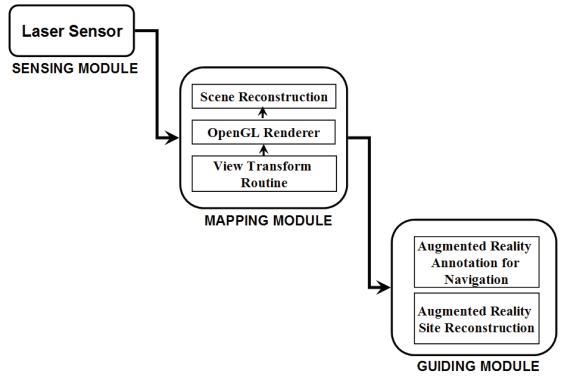


Figure 1 System Architecture

3. SEARCH STRATEGY FOR RESCUE ROBOT

In the design of the system, effective algorithms for both exploration and exploitation are important. When it is required to build an AR system, raw images captured from the camera need to be properly aligned in a common spatial domain. The location where the image is taken is determined by the location of the mobile robot. In this work, the robot position is estimated using a combination of wheel encoders and a laser scanner. The position

of the robot is cast as a state vector $\mathbf{x}_k = [x_k, y_k, \phi_k]^T$, where (x_k, y_k) is the location with reference to a global coordinate, ϕ_k is the robot orientation and k is the time index. By assigning the initial robot location as the origin of the coordinate, the wheel encoder (odometry) returns the velocity and turn-rate describing the motion of the robot and infers its future positions. However, the odometry may drift and positional errors may accumulate over time. Therefore, external sensing is required to correct such induced error. A laser scanner is used and gives discrete range-bearing measurements to the fixtures in the building. The location of each scanned point is inferred from the robot position as

$$\begin{aligned} x^i &= x_k + r^i \cos(\phi_k + \theta^i) \\ y^i &= y_k + r^i \sin(\phi_k + \theta^i). \end{aligned} \tag{1}$$

Salient features, e.g., corners, are then extracted as landmarks and their corresponding range-bearings are fed to an extended Kalman filter (EKF) for estimations of the robot position. By using the EKF as a noise filter for odometry errors, the robot position accuracy is then improved.

The EKF proceeds in the following recursive steps:

Predict:

$$\begin{aligned} \mathbf{x}_{k+1|k} &= \mathbf{f}(\mathbf{x}_{k|k}, \mathbf{u}_k) \\ \mathbf{P}_{k+1|k} &= \nabla \mathbf{f} \mathbf{P}_{k|k} \nabla \mathbf{f}^T + \nabla \mathbf{u} \mathbf{Q} \nabla \mathbf{u}^T, \end{aligned} \tag{2}$$

Measure:

$$\begin{aligned} \mathbf{z}_k &= \mathbf{h}(\mathbf{x}_{k|k}, \mathbf{R}) \\ \nu &= \mathbf{z}_k - \mathbf{h}(\mathbf{x}_{k+1|k}, \mathbf{0}), \end{aligned} \tag{3}$$

Update:

$$\begin{aligned} \mathbf{x}_{k+1|k+1} &= \mathbf{x}_{k+1|k} + \mathbf{K}\nu \\ \mathbf{P}_{k+1|k+1} &= \mathbf{P}_{k+1|k} - \mathbf{K}\mathbf{S}\mathbf{K}^T \\ \mathbf{S} &= \nabla \mathbf{h}^T \mathbf{P} \nabla \mathbf{h} + \mathbf{R} \\ \mathbf{K} &= \nabla \mathbf{h}^T \mathbf{P} \mathbf{S}^{-1}, \end{aligned} \tag{4}$$

where the time indices *k+1* denotes a future time step, $\nabla(\cdot)$ is the jacobian of the corresponding function, for example, see the developments in [7]. Note that the location and orientation of the robot is given by the first 3 elements of the state vector $\mathbf{x}_{k+1|k+1}$ and the rest denote the locations of landmarks in a Cartesian-coordinate.

After the availability of accurate robot positions, objects such as edges in an image frame are detected, e.g., by using a segmentation algorithm [10]. These edges are spatially matched to the laser scan counterparts and a location can then be assigned to the image feature. Given the image objects and locations, the AR routine, e.g., OpenGL is used to generate aggregated scenery of the building interior.

4. EXPERIMENTAL RESULTS

The section presents preliminary experimental results, obtained from a laboratory environment, verifying the performance of the developed algorithm.

A simulation environment in C++ using OpenGL Library was implemented to measure the performance of the proposed algorithms. The environment is constructed with random locations of obstacles and objects. The dynamic objects are allowed in the environment. The results show that the proposed strategies are complete and promising for the main goal of the robot. The number of steps to find the reachable objects is smaller than that of the traditional mapping method. Typical images captured in an indoor built environment are shown in Figure 2 where vertical edges from the fixtures are noticeable and detected as inputs to the AR routine.

Figure 3 shows cases where the robot is driven in the same laboratory while moved on a circular trajectory with a number of repetitions. The figure also depicts the boundaries of the laboratory which are obtained from aligned laser scans by the EKF recursive procedure. The robot is indicated by a triangle and the uncertainties of the landmarks are illustrated by the associating ellipses.

The relative distances between the landmarks, in pairs, are shown in Fig. 4 in a mesh landscape format. The x-and-y axes denote the landmark index and the z-axis gives the distances in meters. Operators can obtain a particular separation between any two landmarks by using a user-graphic-interface. The results presented herein

show that the proposed approach is complete and satisfactory for the assigned inspection task.

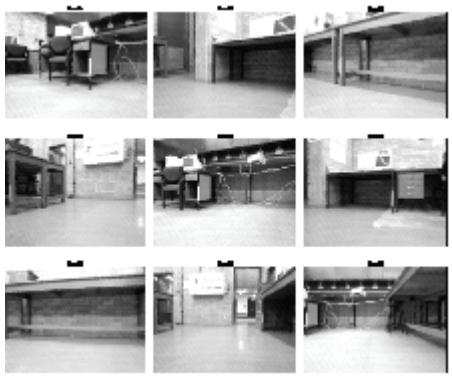


Figure 2 Typical Building Interior Scenario (images are shown in steps of 50 frames)

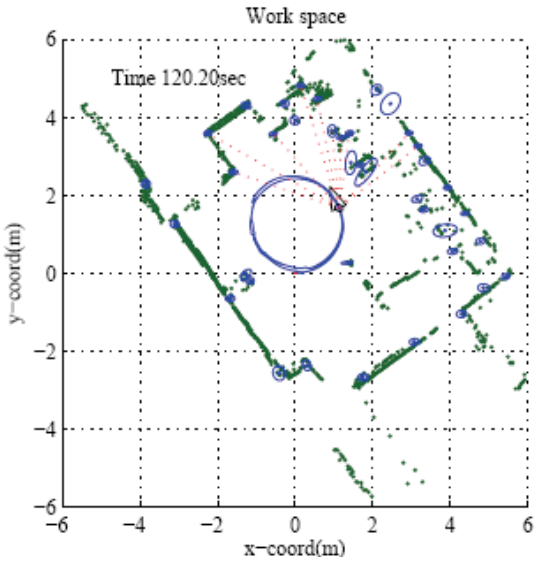


Figure 3 Typical Robot Trajectories and Potential Edge Features (the robot indicated by the triangle started at x=0,y=0)

5. CONCLUSIONS

This paper proposed an autonomous inspection system for building interiors. A mobile robot is equipped with a camera where the captured images are used to build an Augmented Reality system. Operators may tele-operate the robot and are provided with enriched information from AR for efficient inspections. A novel autonomous planning strategy suitable for intelligent robot architectures is proposed. The performance of the approach is assured by using a laser scanner and an extended Kalman filter (EKF) to provide an accurate position estimate of the robot. Preliminary results obtained from a laboratory environment are satisfactory.

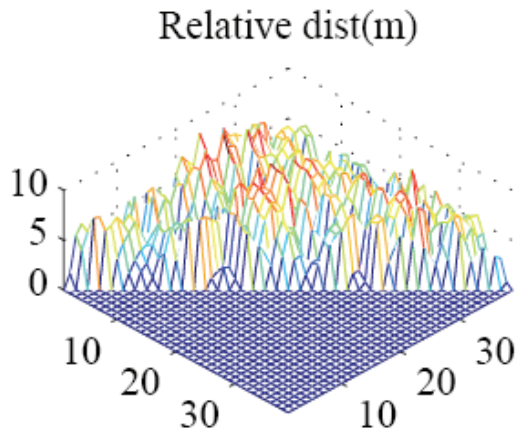


Figure 4 Relative Distance Between Landmarks

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Construction Automation Group, I.I.T. Madras

DEVELOPMENT OF A HYBRID DEVICE BASED ON INFRARED AND ULTRASONIC SENSORS FOR HUMAN RESOURCE MANAGEMENT

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ABSTRACT

Human resources are continuously gaining importance in association with construction site management. With increasing interest being shown in the use of state-of-the-art technologies such as radio frequency identification (RFID) in site management, we developed a device based on infrared radiation and ultrasonic sensors for application in the management of human resources, especially labour safety management. We tested sensors and optimized the sensing range and angle of the device, which could detect workers using an infrared sensor that senses body heat and an ultrasonic sensor to measure the object's distance. The device allows a manager to determine where workers are, and how far they are from the point of sensing. This paper shows that the device can prevent fatal accidents such as falls. In doing so, it addresses a key issue in the management of safety on work sites.

KEYWORDS

Safety Management, Infrared Sensor, Ultrasonic Sensor

1. INTRODUCTION

Human resource management has been identified as very important for site management compared with such management at other locations. Because the management of the workforce has a direct impact on project performance, many researchers have presented management methods. For example, Brandenburg (2006) presented a management strategy for human resources to improve overall productivity, including labour safety and the success of the project [1]. Thomas (2006) suggested fundamental principles of workforce management for utilizing the workforce efficiently [2].

Hardware approaches to management methods are limited, especially in labour safety management,

which occupies an important position in human resource management. To manage labour safety, many researchers have developed a coding system to facilitate the categorization of fatal falls to determine the importance of contributing factors and to derive effective protection strategies [3]. They have determined the causes of construction fall accidents and identified any particular patterns related to fall accidents [4]. However, there are limited techniques for finding out whether workers are exposed to danger and how far they are from a point of danger. Such a technique would allow labour safety to be managed directly and actively.

Therefore, we propose a state-of-the-art device combining infrared (IR) and ultrasonic (US) sensors for labour safety management on construction sites. This device is remarkably useful in detecting careless workers exposed to dangerous situations and making them aware of the danger, thereby reducing accidents resulting in fatalities. To identify the capacity and performance of the device, as shown in Figure 1, we tested it as follows. (1) We collected background information about IR and US sensors to discover their technical features and application status. (2) We proposed an approach to develop the device based on infrared radiation and ultrasonic technologies. (3) We optimized the sensing range and angle of the device that can detect workers, with the IR sensor sensing body heat and the US sensor measuring distance. (4) Finally, we present the feasibility of the detecting device combined with US and IR sensors (DEUI) to apply it to managing labour safety.

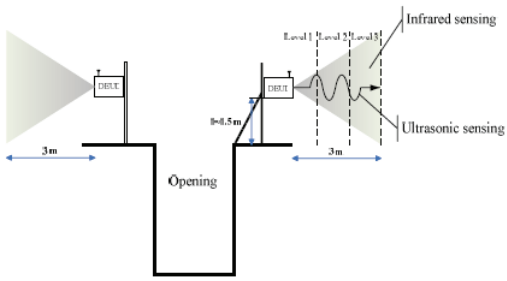


Figure 1 Performance of the Device

2. BACKGROUND

2.1 Ultrasonic (US) Sensor

US technology covers an enormous range of human endeavour, from non-destructive testing (NDT) to medical scanning; from chemical analysis to (alleged) nobbling of race horse; from welding to flowmeters [5].

US sensors utilize transducers that transform an electrical signal into a US wave and vice versa; in other words, the basic idea is that they transmit acoustic waves and receive waves after interaction between the US wave and the investigated process [6], [7]. Ultrasound covers a frequency range from 20 kHz to about 1 GHz. For technical applications, the range 20 kHz to 10 MHz is the most important.

Hauptmann (2002) classified US sensors and presented their features: non-invasive measurement, inline measurement, rapid response, low power consumption, excellent long-term stability, and high resolution and accuracy [7]. With the features, he also presented various applications of US sensors such as temperature measurement, pressure measurement, level and distance measurement, and flow measurement.

We used US sensors to determine the presence of workers and to measure their distance from the sensor. US has general application to level measurement, proximity detection, and robotics.

2.2 Infrared (IR) Radiation

IR sensors are widely used as proximity sensors and offer lower cost and faster response times than US sensors [8]. The coming of age of IR technology has opened the door to a variety of applications in electrooptic devices, premises security systems, communication systems, data transmission systems, missile warning systems, pollution monitoring sensors, and so on [9].

IR sensors can be classified as photon sensors or thermal sensors. In a photon sensor, the absorbed radiation excites electronic transitions within the material and the observed electrical output signal results in some way from the changed electronic energy distribution, while in a thermal sensor the incident radiation is absorbed and changes the temperature of the material, the signal being

observed as a change in some temperature-dependent property of the material [10].
In this paper, a pyroelectric infrared ray (PIR) sensor was used, a type of thermal sensor that detects infrared radiation from body heat and is of general application to security or households.

3. DEVICE CONFIGURATIONS

The DEUI is an enhanced safety supervision method that can prevent fatal accidents such as falls. It consists of ultrasonic and infrared sensors, a speaker, and a main board. As shown in Figure 2, they can be operated by a rechargeable battery.

3.1 Ultrasonic (US) Sensor

US sensors have been used to determine the presence of workers. For testing, SensComp's 600 Series Instrument Transducer for operation in air at ultrasonic frequencies was used [12]. One reason why this sensor was chosen is that it is very applicable as it can detect soft targets such as clothes without absorption. It has a beam angle of 15° and features ranging capability from 2.5 cm to 15.2 m.

3.2 Infrared (IR) Sensor

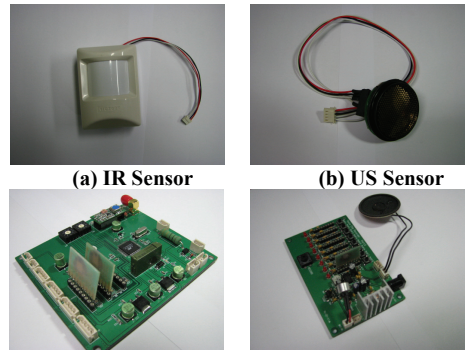
It is important for US sensors to determine the presence of people when measuring distance, not other objects such as steels or other materials. Therefore, it is necessary that an IR sensor determines whether an object is human or not by sensing body heat.
In this test, Vessco's PIS-700 passive IR detector was used to sense IR radiation from body heat. It is of general application to security or households [13]. Its maximum coverage angle is 130° and its sensitivity can be controlled.

3.3 Recorder, Speaker and Main Board

The device consists of sensors and a speaker, which can send a beep or a spoken message to people approaching the device, depending on the distance measured by US sensors from it. The voice or any other sound can be recorded very easily.

We divided the controlled space into three zones. The first zone is 2–3 m from the device, the second zone is 1–2 m from it, and the third zone is 0–1 m from it. When a worker is in the first zone, the speaker beeps. If the worker enters the second zone, it beeps faster. Finally, when the worker is in the third zone, the speaker sends a recorded voice message. This should alert a person approaching the DEUI to his or her increasingly dangerous situation.

The main board controls the interaction between the two sensors: when the IR sensor detects a person, the US sensors measures his or her distance from the DEUI, and the main board makes the speaker send out a recorded voice message such as "STOP".



(a) IR Sensor (b) US Sensor
(c) Main Board (d) Recorder and Speaker

Figure 2 Device Configurations

4. TESTS

4.1 Test Plan

The features of the two sensors such as sensing angle and range and their interactions in some situations are considered to optimize their incorporation in the device. We also tested the point at which the speaker should broadcast its voice message to find the detected distance from the DEUI, as shown in Figure 3. The following tests were conducted:

(1) Scenario test
(2) Optimizing range of sensors test
(3) Classifying detected zones test

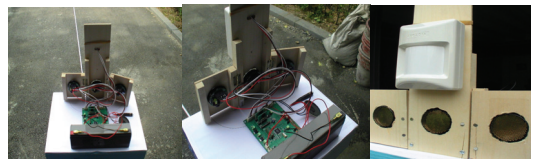


Figure 3 Test Model

4.2 Scenario Test

The purpose of the scenario test is to investigate whether the US sensor detects obstacles such as walls rather than people. Therefore, some conditions were imposed as illustrated in Figure 4: near an opening with a wall on one side; near an opening with walls on two sides; or near an opening with no walls.

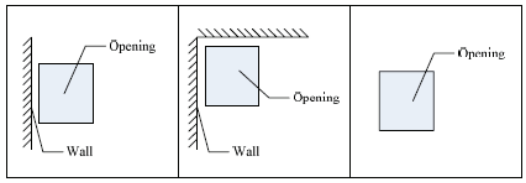


Figure 4 Test Conditions

4.3 The Sensor Range Test

The IR sensor was tested to confirm that it could sense body heat at ranges up to 3 m. A man moved very slowly while we checked the point at which the sensor could detect him. When he was detected, a light was turned on. Using the light, the range and angle of the IR sensor were checked.

The US sensor was set up to detect the presence of a tester and to measure the distance. It was configured to detect a person after the IR had sensed body heat. When the sensor had detected a person, the speaker broadcast a recorded beep and a voice message. Thus, we could check the range and detection angle of the US sensor by using the sound. Considering the US sensor's optimal angle, three US sensors were used with one IR sensor.

4.4 Classifying Detected Zones

The purpose of this test is to see how quickly the DEUI could detect a person and the point at which the person was detected. The DEUI was set up so that when it detected a person, it sent out a different recorded sound or voice depending on the zone where the person was detected. Three detection zones were used: 0–1 m, 1–2 m, and 2–3 m from the device. We checked that different sound and voice signals were sent out for detection in each zone, to indicate the danger level. We used this test to optimize the detection zones.

5. RESULTS AND DISCUSSION

We tested the DEUI to alert careless workers to dangerous situations. The test showed that the IR sensor had an angle of 120° and detected a tester up to 3 m from the device. The optimal detecting distance was determined to be about 3 m away from the device because it should detect workers before they are very close to dangerous places.

The US sensors, on the other hand, had sensing angles of 15° each, and as illustrated in Figure 5(b), we controlled their angles to be the same as the IR sensor's. When the three US sensors were adjusted to adapt to the IR sensor's angle, a dead zone was found within the range of the IR sensor. However, the device seldom recognized the dead zone when a tester was moving. Therefore, the US sensors' coverage was adjusted to about 120°, like the IR sensor's, as shown in Figure 5(a).

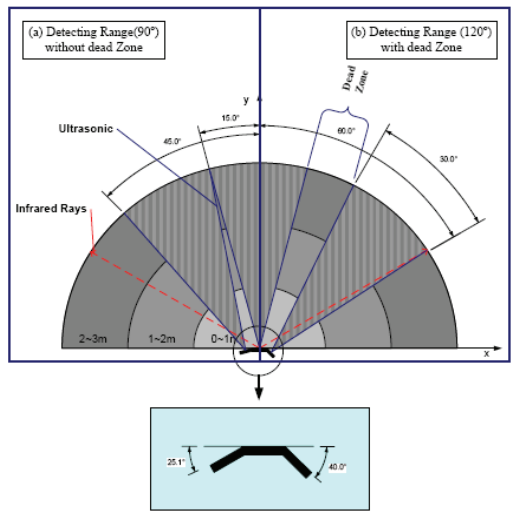


Figure 5 The Results of the Test

When the IR sensor detected a tester's body heat, the US sensors operated to detect his distance and the speaker warned him depending on the zone. However, the US sensors did not operate when the IR sensor could not detect body heat. That meant that although the DEUI was blocked by walls or other materials, the US sensors could not operate, and the speaker remained quiet because no body heat was sensed by the IR sensor. However there was limitation that when IR sensor sensed body heat, US sensor detected not only human but also other objects and their distance

such as a wall and sent out the recorded sound regardless of human's location.

The results show that the DEUI can be applied to labour safety management. It detects workers who are approaching dangerous places such as water purifier tanks or openings in the construction site and alerts them to the dangerous situation. It can be expected that this active method will help reduce fall accidents and will help site managers supervise safety in the construction industry. Furthermore, it can be operated by a rechargeable battery and thus it can be set up anywhere very easily. Moreover, it should be possible to notify safety managers of detected dangerous situations via wireless data acquisition technologies such as radio frequency modems. This will make labour safety management effective and will help improve human resource management at construction sites.

6. CONCLUSION

This paper tested a DEUI to detect workers exposed to dangers on construction sites and to alert them to their situation. Our tests anticipated an active method to prevent accidents on construction sites, and our device could contribute to labour safety. Even though workers may not pay careful attention to dangerous situations, the device can prevent fatal accidents such as falls.

7. ACKNOWLEDGMENT

This work was supported by the Second Brain Korea 21 Project.

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ROBOT TECHNOLOGY AND APPLICATIONS

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ACTIVE CONTROL OF INDOOR ENVIRONMENTAL QUALITY

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ABSTRACT

This paper presents a methodology for the integrated control of Indoor Environmental Quality. The most important aspect of the methodology is the treatment of the task as a multi-objective optimization problem. Appropriate control actions that achieve reasonable tradeoffs among conflicting objectives are selected through multi-objective optimization in which predictive models are trained using machine learning techniques. The methodology is currently being implemented and tested in the Field Environmental Chambers (FEC) of the Department of Building, National University of Singapore.

KEYWORDS

Building Automation, Control, Multi-Objective Optimization, Indoor Environmental Quality

1. INTRODUCTION

Automatic controllers promise to improve energy efficiency and reduce maintenance costs. For example, a system called NEUROBAT (Morel et al., 2001) obtained energy savings of 13% (compared to conventional open loop controllers) in two occupied rooms during a complete heating season. Other examples of the use of automatic controllers for thermal comfort can be found in Chen (2001), Kummert (2000) and Chow et al. (2002). Guillemin and Morel (2002) developed a prototype that simultaneously controlled heating and lighting. Since such systems are still being tested in laboratories, they have not penetrated the industry. Commercial Heating Ventilating and Air-Conditioning (HVAC) systems operate through taking actions sequentially in order to meet targets related to individual parameters. Integrated control of diverse indoor environmental quality (IEQ) parameters such as temperature, lighting level, relative humidity and carbon dioxide (CO_2) do not exist as commercial products.

In most of the systems described above, control is treated as a single objective optimization problem. Parameters that influence indoor environmental quality such as temperature, humidity, level of CO_2 and lighting can be adjusted through operating individual devices. But it is not easy to obtain the right combinations of values of these parameters since operating a single device might have several effects. For example, suppose that the objective is to improve the level of lighting in a room. When other objectives are ignored, the most economic solution will be to draw open the window blinds. However, this brings more radiant heat into the room and consequently, the cooling load increases. When there are multiple objectives, we need to search for solutions that make compromises among conflicting objectives.

There are many researchers who have studied the influence of interacting parameters on the indoor environment quality, for example, Suter et. al. (2007); and Mahdavi and Unzeitig (2005). In these works, multiple parameters are modelled for the purpose of simulation and performance evaluation, but not for adaptive control. Multi-objective optimization approaches such as Pareto optimization have never been investigated for the control of IEQ. These techniques have been successfully applied to other domains such as structural control (Adam and Smith, 2005). Recent theoretical advances in the area of multi-objective

control make it possible to identify solutions that achieve reasonable trade-offs amongst conflicting objectives such as minimizing energy and maximizing comfort.

This paper presents a methodology for integrated control of IEQ parameters through multi-objective optimization. The primary contribution of this paper is in the area of building automation and control. A new control strategy that maximizes building performance has been developed. The most important aspect of the methodology is the treatment of the task as a global optimization problem. The methodology is currently being implemented and tested in the Field Environmental Chambers (FEC) of the Department of Building, National University of Singapore. This paper reports work that is in progress and focuses mainly on the theoretical framework.

2. INTEGRATED CONTROL OF IEQ

The perception of indoor environment quality is influenced by many aspects such as thermal comfort, air quality, and lighting. Air quality may be measured through a number of parameters such as relative humidity (RH), level of CO_2, velocity of air movement, etc. Traditionally, HVAC systems control the air quality and thermal comfort using parameters set by users. In most cases, the only parameter that the end-user can set is the temperature. The air conditioning system provides adequate supply of cold air into the room such that the required temperature is attained. The amount of cold air supplied to a room is regulated by opening and closing of dampers to various levels that are determined by the control algorithm. The supply of cold air indirectly influences other parameters such as RH and CO_2. Accurate simultaneous control of these parameters is not possible through this approach. In fact, these parameters are not even measured in the conventional systems.

In the present work, all the important IEQ parameters are measured by appropriate sensors. Measured IEQ parameters include temperature, RH, CO_2 and lux. In addition, energy consumption of individual subsystems are also measured using power meters.

The room is equipped with a number of actuators that perform different functions. These include dampers that let in cold air into the room, dampers that control the in-take of fresh air from outside, switches that control lighting illuminance and position regulators of blinds.

Data from sensors is used to identify the most appropriate control action through multi-objective optimization. The complete feedback loop is shown in Figure 1.

3. MULTIOBJECTIVE OPTIMIZATION

The control task is treated as a multi-objective optimization problem. Instead of optimizing a single objective, multiple objectives are considered simultaneously. There are objectives related to attaining desirable values of IEQ parameters as well as minimization of energy. The goal of active control is to achieve the objectives to the maximum extent possible. Since objectives frequently conflict with each other, multi-objective optimization should aim at achieving reasonable trade offs. For example, it may not be possible to attain the set values for both the temperature and RH, since excess humidity is usually removed by cooling the air which tends to lower the temperature below the set values. In such situations, the optimization algorithm has to identify the best control action that will achieve reasonable compromises. This is not an easy task.

There are several approaches to multi-objective optimization. One popular approach is called Pareto optimization and is adopted here. In this approach, a population of solutions known as the Pareto set is generated (Raphael and Smith, 2003a). The Pareto set (front) consists of a set of solutions that satisfy what is known as the Pareto optimality criterion. According to this criterion, a solution point P (Figure 2) is accepted only if there are no solutions better than P with respect to all the objectives. For example, even if P is worse than another solution P1 with respect to one objective, P is accepted provided that it is better than P1 in at least one objective. Thus each Pareto optimal solution is good in some respect. The set of all Pareto optimal solutions form the Pareto set or Pareto front.

Many techniques for generating the Pareto front are found in the literature. These include multi-

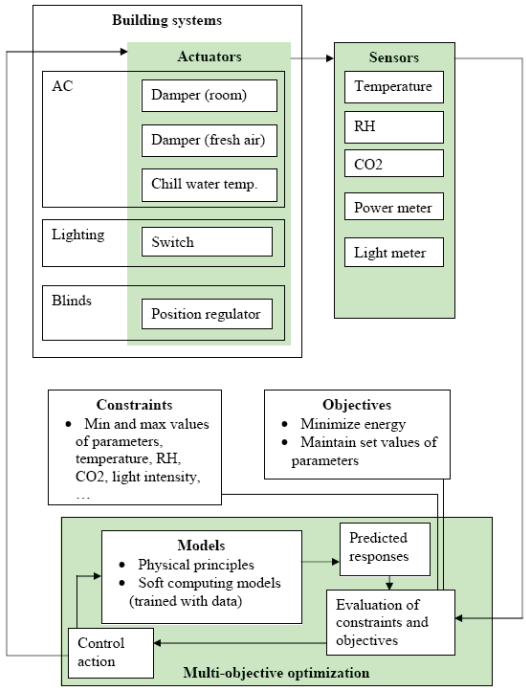


Figure 1 System Architecture

objective versions of genetic algorithms (Haralampidis et al., 2005, Deb and Tiwari, 2005, Grierson and Khajehpour, 2002), simulated annealing (Czyzak and Jaszkiewicz, 1998, Ulungu et al., 1999), weighting methods (Kim and Weck, 2006), and multi-start methods (Jaszkiewicz 2002). In this work, a newly developed algorithm (Raphael 2006) is used to generate the Pareto front. This algorithm divides a multi-objective optimization problem into a series of single objective optimization problems that are easier to solve. This is done by selecting one objective at a time and treating remaining objectives as

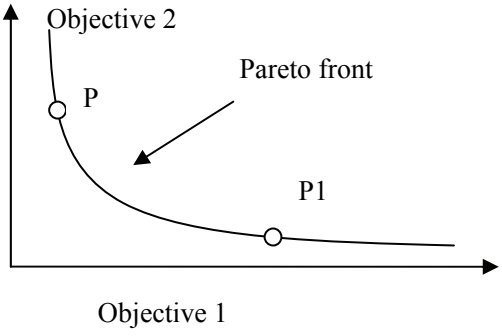


Figure 2 Pareto Front

constraints. It has been shown that this algorithm is able to generate good quality Pareto fronts. Another attractive feature of this algorithm is that it has a mathematical proof of convergence.

Once the Pareto front is generated, a suitable solution point can be selected using a number of heuristics. A simple heuristic is to select the point on the normalised Pareto surface where the slope is close to 45 degrees. This is the point where the relative gain in one objective is compensated by an equivalent loss in the other objective.

4. MACHINE LEARNING

The objective functions that are used in the optimization compute the difference between desired states and the predicted states after the application of a control action. This requires an accurate prediction of the effects of control actions. In general, the effects of control actions cannot be predicted accurately since closed form equations are not available and theoretical models involve many parameters whose values are not known precisely. In these circumstances, machine learning techniques are used to train models to be used for prediction. Two types of models are used. The first type is based on physical principles, but contains parameters whose values are not known precisely. The values of parameters are determined through a process known as model updating in which the best combination of values of parameters is found through the minimization of prediction error. The second type of models is purely empirical and is obtained through training artificial neural networks.

An example of the first type of model is the energy balance equation which predicts the change in the average temperature of the room due to the opening of the damper by a unit amount. Parameters in the model whose values are unknown include the heat influx into the room, temperature and velocity of incoming air, etc.

An example of an empirical model is the computation of air velocity at a specific location of room. Accurate determination of air velocity requires complex analysis using computational fluid dynamics. However, a reasonable approximation might be obtained in a given setting through empirical observations, including previous

observations where air velocities have been determined.

A model updating procedure similar to Robert-Nicoud et. al. (2005) has been adopted in this project. In this approach, the error between model predictions and measurements is minimized using a global search algorithm called PGSL (Raphael and Smith, 2003). The procedure results in the identification of a population of candidate models. The characteristics of this population are studied in order to evaluate the reliability of identification and to determine whether a unique model explains the data.

Conventionally, model identification is treated as an optimization problem. The model whose prediction has the minimum error with respect to measurements is chosen as the best model. I has been shown in Robert-Nicoud et. al. (2005) that this procedure results in the identification of wrong models in the presence of modelling and measurement errors. This is because different types of errors might compensate for each other such that the next error is very small. In order to avoid this problem, it is important to compute the error threshold through an estimate of modelling errors and sensor precision. All the models whose predictions lie below this threshold are chosen as candidate models. An examination of the variation in the values of model parameters will reveal whether a unique identification is possible. For example, if model parameters show wide variation, it means that many different models match observations within the error threshold. In such a situation, we need to install more sensors or increase the precision of sensors.

5. CURRENT STATUS

Two field environmental chambers (FEC) are currently being equipped with sensors and actuators using the European Installation Bus (EIB) technology. EIB is a building automation system founded in the late eighties with the support of a number of major European manufacturers such as Siemens, Gira, Jung, Merten, and ABB. It is being widely used in Europe and is increasingly being used in other parts of the world. Even though it is currently used mainly for controlling home appliances such as lighting, water heaters and security cameras, the flexibility offered by this technology makes it possible to control any type of electrical device. The EIB system consist a bus control cable installed in addition to and parallel to the power supply cable. EIB devices such as switches and sensors are connected to the bus. The bus is the common communication medium. Readings from sensors can be obtained through a computer connected to EIB. Control commands to actuators can also be sent from the computer through the bus. This makes it possible to develop customised control applications that operate on these devices. Existing HVAC components in the FEC are in the process of being interfaced with EIB devices.

The multi-objective optimization routine has been fully developed and has been tested on a number of benchmark problems. However, the control strategy needs to be fine tuned and it cannot be evaluated at this stage since reliable data has not been obtained yet. Model development and testing are still in progress. Preliminary results are expected in the coming months.

6. CONCLUDING REMARKS

The main contribution of this paper is a methodology for the integrated control of IEQ. Instead of making decisions using the values of individual parameters, control is treated as a multi-objective optimization problem. Control actions are selected such that there are reasonable trade-offs among conflicting objectives. This is achieved through Pareto optimization. The selected actions are applied by sending commands to appropriate actuators. Responses to these actions are recorded by sensors and are input into the optimization module to complete the loop. It is an innovative feedback control system that simultaneously takes into account multiple objectives.

7. ACKNOWLEDGMENTS

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INTELLIGENT WINDCATCHER - A COMBINATION OF MODERN AND TRADITIONAL TECHNOLOGY

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ABSTRACT

In this paper, a novel idea to prepare indoor fresh air by an environmentally friendly way is proposed. In this design we are inspired by traditional windcatchers which have been being used for centuries in torrid region of Iran. Theirs unique feature of in-dependency to costly energy sources have made them suitable choices specially for not fully developed areas. We devised an intelligent windcatcher which can adapts itself according to outside weather conditions to maximize the performance of indoor air conditioning. Design procedure in addition to simulation results are presented and the advantages of the proposed design are discussed.

KEYWORDS

Windcatcher, Badgir, Fuzzy Controller

1. INTRODUCTION

A windcatcher, or *Badgir* (in Persian), is a traditional Persian architectural device have been used for several centuries to create natural ventilation in buildings. It is not known who first invented the windcatcher, but it still can be seen in many countries today. Windcatchers come in various designs, such as the unidirectional, bidirectional, and multi-directional.

The windcatcher functions on several principles: First, a windcatcher is capped and has several directional ports at the top (Traditionally four). By closing all but the one facing away from the incoming wind, air is drawn upwards using the *coanda* effect, similar to how opening the one facing the wind would push air down the shaft. This generates significant cooling ventilation within the structure below, but is not enough to bring the temperature below ambient alone - it would simply draw hot air in through any cracks or windows in the structure below. Therefore, he key to generating frigid temperatures seems to be that there are very few cracks at the base of the thick structure below, but there is a significant air gap above the *qanat*. A qanat has quite a lot of water inside, because there are frequent well-like reservoirs along its path. Completely shaded from the sun, a qanat also aggregates the cold, sinking air of the night, which is then trapped within, unable to rise up to the less dense surface air. A windcatcher, however, can create a pressure gradient which sucks at least a small amount of air upwards through a house. This cool, dry night air, being pulled over a long passage of water, evaporates some of it and is cooled down further. Finally, in a windless environment or waterless house, a windcatcher functions as a stack effect aggregator of hot air. It creates a pressure gradient which allows less dense hot air to travel upwards and escape out the top. This is also compounded

significantly by the day-night cycle mentioned above, trapping cool air below. The temperature in such an environment can't drop below the nightly low temperature. These last two functions have gained some ground in Western architecture, and there are several commercial products using the name windcatcher. When coupled with thick adobe that exhibits high heat transmission resistance qualities (R-value), the windcatcher is able to chill lower level spaces in mosques and houses in the middle of the day to frigid temperatures [1].

So effective has been the windcatcher in Persian architecture that it has been routinely used as a refrigerating device (*yakhchal*) for ages. Many traditional water reservoirs are built with windcatchers that are capable of storing water at near freezing temperatures for months in summer. High humidity environments destroy the evaporative cooling effect enjoyed in the dry conditions seen on the Iranian plateau; hence the ubiquitous use of these devices in drier areas such as Yazd, Kashan, Nain, and Bam. A badgir is depicted in Fig. 1.



Figure 1 Badgirs in Persian Cities

2. PROPOSED DESIGN

In this paper, a novel idea for embedding a cheap cooling system in buildings is proposed. In this design, air conditioning energy is totally provided by wind power. Moreover the remained small amount of the energy needed by intelligent system and actuator are gathered from sunlight via mounted solar cells. Also a sealed lead-acid battery (like those used in cars) is charged by solar cells and provide the auxiliary power source for nights or cloudy days. So there is no need to other costly energy sources.

The proposal is based on traditional windcatchers which are even now in use in some of Iran cities which are near deserts. In this design, the intelligent windcatcher has the ability to rotate freely in 360 degree by means of a rotating shaft. In order to reduce the necessary torque to move the shaft, a gearbox is devised. The gears around the windcatcher make the gear with large radius and the gear with small radius is coupled to motor-gearbox actuator. So the rotation of the windcatcher can be performed even with a small DC motor in this way. The mentioned DC motor is energized by a PWM driver circuit which amplifies the control action signals and get it to motor with high efficiency and little thermal waste. The base controller is a classic PI (*Proportional-Integral*) controller that forms a feedback control scheme by using the error signal made by subtracting the windcatcher direction sensor's signal θ_L from reference direction signal θ_r .

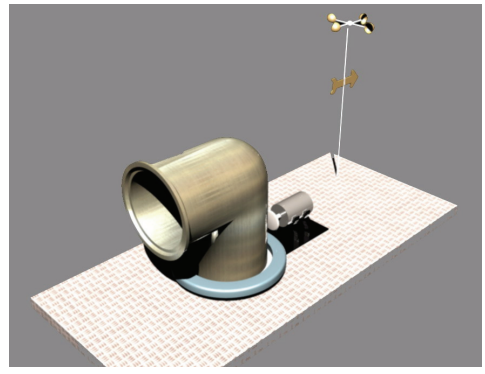


Figure 2 3D View of the System

The reference direction signal is obtained from the Fuzzy supervisory controller. The fuzzy controller decides intelligently in which direction and to what position should the windcatcher rotate. The Fuzzy Controller make its decisions by analyzing the sensors information. We employed several sensors to get the information about wind direction, wind speed, ambient temperature and battery voltage. All of these information help the Fuzzy controller to make correct and optimal decisions...

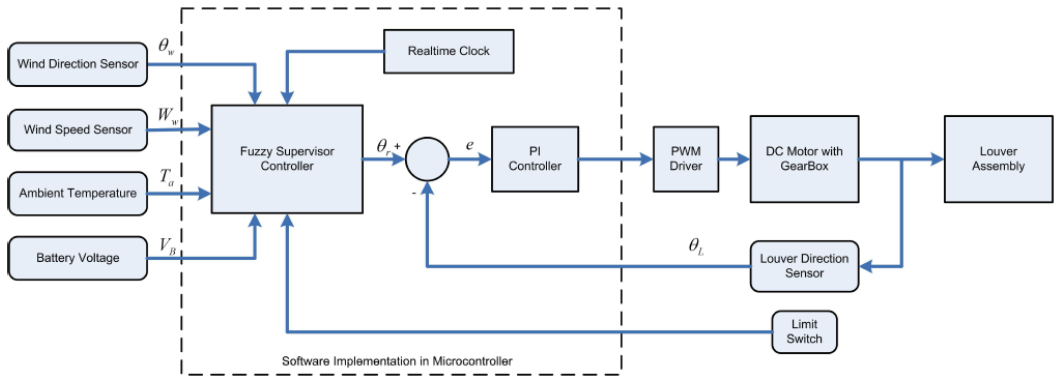


Figure 3. Complete System Diagram

Required electrical energy is completely provided using small-in-size solar cells. However to ensure that the system is always online, an other backup system is mounted which is actually a 12 volt sealed Lead-Acid battery. The implementation of the proposed controllers can be done using a microcontroller circuit with sufficient input and output channels. We have selected PIC16F877A microcontroller to this purpose. The overall block diagram of the system is given in Fig. 3.

Design and simulation of the electrical circuit is done using PROTEUS software package. Next, The both PI and Fuzzy controllers are designed and simulated using MATLAB. At the following sections, more detail on the structure of the proposed windcatcher, control system, electronic circuits and instrumentation equipment are discussed.

2.1. Structure

This system composed of five different parts, namely: 1. The entrance part which guides the wind into the building, 2. An electric DC motor which provides the required force to track the changes in wind direction, 3. Weather station consists of wind speed sensor and wind direction sensor, 4. Control unit and 5**.** Power unit which consists of a sealed lead-acid battery and a solar-cell panel**.**

The moving part of the windcatcher is connected to its non-moving part with a flange style coupling which has a ball bearing mechanism between these two parts. So the moving part can rotate freely around its axis. In order to prevent the ball bearing mechanism from dust and to preserve the lubrication, two flexible covers are used on both inner and outer section of coupling.

In the center of the channel there is a shaft connected to both moving and non-moving parts and provides the structural stability of the system**.**

The rotation force of the windcatcher comes from the teeth of the DC motor which are coupled to the teeth of movable part's flange**.** The DC motor is not active all the time and it only activates in predefined periods to adjust the direction of the windcatcher. In order to increase the performance of the system some strategies can be added. First of all a humidifier should be considered in the channel. This humidifier can be a wet basement channel or an artificial humidifier. Moreover by using output ways for air, the efficiency of the system will increase through better circulation of the air. Also the output ways can act as a suction system by mounting a dome with a hole on its uppermost curve. This structure is originated from Persian architecture. The air circulation in some places such as bazaar, traditional bathrooms, reservoir and so on are maintained by such a mechanism**.**

2.2. Instrumentation

In this design there are 6 sensors which prepare the essential information for the windcatcher controller. These information are direction of windcatcher, wind direction, wind speed, outdoor temperature, battery voltage and a limit switch respectively.

The measurement of the windcatcher direction is done by an optical encoder coupled to the DC motor's gearbox. Similarly, another encoder is installed to detect the wind direction. Near the wind direction sensor a tachometer coupled to a propeller measures wind speed. A cheap IC thermometer prepares the outdoor temperatures information. This sensor should be installed in a way that it is protected from direct sunlight. The limit switch provides the reference direction to the controller when it is turned on. The sensory part of this design especially for wind speed/direction and ambient temperature can be simplified by using a weather station package which can be purchased from markets. There are different types of weather stations with wide range of prices but for this application just a simple one that provides the mentioned data is sufficient. Those who give data by a standard serial port like RS232 are preferred.

2.3. Electronic and Control Design

To control the direction of windcatcher system, first of all we should define an angle which indicates the position of this windcatcher.

The reference angle is in fact the determinative factor in position of windcatcher. The high efficiency is achievable when the windcatcher stands in correct direction. But the challenge is that how to determine this direction. Before getting in deterministic description of problem, let me clarify the subject conceptually. In hot weather, when the wind is blowing slightly, the intake of windcatcher should be oriented directly into the wind so that a proportion of the wind finds its way into the mounted channels and by passing through wet basement channel cooled and finally passes inside the house and prepares fresh air conditioning. As the wind speeds up, the windcatcher should changes its direction according to the winds orientation to control the amount of air coming indoor until that the normal wind changes into storm. At that case the controller changes the windcatcher's intake direction and positions it opposite to the wind direction so the wind passes the windcatcher and don't enter it.

By a quick brainstorming about the windcatcher, it's obvious that the windcatchers are necessary when it's warm. In cold days or nights the windcatcher should be out of operating and this is achievable by means of an intelligent controller.

The Fuzzy controller plays the rule of a supervisory controller and it is admittedly the intelligent part of the design. The classic PI controller is used to prepare the required control action to do the precise tracking of the Reference direction generated by the Fuzzy controller. Its *Proportional* and *Integral* parameters should be tuned according to selected motor's specifications and dynamic of the windcatcher's structure however in this application the performance of the tracking is not emphasized and we just require the tracking controller to do tracking smoothly and precisely for predefined time lapses. So adjusting these parameters to lower levels is more favourable. Further information on designing the Fuzzy controller is given in the next section.

We select PIC16F877A microcontroller from Microchip Inc. to implement the required block diagram. PIC16F877A is a low-cost, high-performance RISC core microcontroller which contains a hardware PWM module, a Watchdog timer and 8 channels ADC [2]. As we need just 5 analogue input channels so without use of any other additional part, the selected microcontroller can perform the required conversion.

2.4. Software

Microcontrollers do the required tasks according to the program written and loaded in their ROMs. In our design we do not want that the system become active all the time because we should use the stored energy precisely and do not waste it. So we decide to do the sampling just in every 10 second and require the system to hibernate between sampling. The collected samples are averaged every 10 minutes and after that the PI controller and PWM driver are activated and electric motor starts to turn the windcatcher to track the changes. By using this technique, effects of the turbulent flow of the wind are minimized and the windcatcher just tracks the overall trend of the wind's direction with a little energy consumption.

The PI controller and PWM driver remain active for about 4 time response of the system to ensures the certain tracking and then they are inactivated and they should wait to the next activation period.

3. FUZZY CONTROLLER

The structure built up here is a two-input single-output controller. The inputs are the speed of the wind W_s and the temperature *temp*. Consequently, the input to the servo mechanism of windcatcher would be the reference angle, which is actually the summation of the wind's angle with the output of the fuzzy controller. The operational structure of the proposed fuzzy controller is shown in Fig. 4. It consists of three building blocks, namely: 1) a *fuzzification* block that expresses quantitative action to qualitative action; 2) a fuzzy inference engine that generates the fuzzy rules; and 3) a *defuzzification* block that articulates qualitative action to quantitative action. Fuzzification translates a numeric value for the speed of wind or temperature into a linguistic value such as high or low with a membership grade [4]. Defuzzification takes the fuzzy output of the rules and generates a "crisp" numeric value used as the control input to the windcatcher.

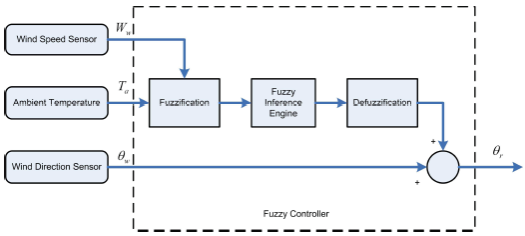


Figure 4 Block Diagram of Fuzzy Controller

The output of fuzzy controller indicates the necessary angular distance between windcatcher's position and wind's direction. In order to get the correct position of windcatcher, the output of fuzzy controller is added to wind's angle. The result is the reference angle which is fed into another linear PI controller to be tracked. The overall system is shown in Fig. 3.

3.1. Fuzzy Membership and Rule Generation

The chief problem of the construction of the fuzzy controller is related to the choice of the regulator parameters. Certainly, there is no systematic procedure for the design of a fuzzy controller (membership functions and rules generation), and this section is devoted to the determination of the fuzzy sets and the linguistic rules. In order to define the number of fuzzy set's for wind speed, first of all we should consider the different kind of winds according to their forces.

1. *Forces 0 to 2:* The wind's speed is up to 11 kilometres per hour and has slight move.
2. *Forces 3 to 4:* The wind moves with the speed of 12 to 29 kilometres per hour. There is a breeze which moves flags and wags the leaves of trees.
3. *Forces 5 to 6:* With this force the wind's speed goes up from 30 to 50 kilometres per hour.
4. Forces 7 to 9: There is a windstorm with the speed of 51 to 87 kilometres per hour.
5. *Forces 10 to 12:* The real storm happens with the speed of 88 to 118 kilometres per hour which cause widespread wrecks and destruction.

By using this knowledge about wind, the fuzzy sets for wind speed are defined as follows:

- **N** (Normal): up to 20 km/h
- **SL** (Slight): from 20 to 50 km/h
- **ST** (Strong): from 51 to 88 km/h
- **STO** (Storm): upper than 88 km/h

The number of the linguistic sets of the temperature is defined by three simple state, namely: hot H ,moderate M ,and cold C. Additionally, four linguistic sets, i.e. D, $30D$, $60D$, and ID, have been chosen for the output variable of the fuzzy controller structure.

The scaled input and output membership function sets are shown in Fig. 5 and 6. To obtain the control decision, the Mamdani's inference method is used [3]. It is based on the minimum function to describe the **AND** operator present in each control rule and the maximum function to describe the **OR** operator. The output of the fuzzy controller structure is crisp, and thus, a combined output fuzzy set must be defuzzified. To express the qualitative action in a quantitative action, the sum-product composition method was used. It calculates the crisp output as the weighted average of the centroids of all output membership functions.

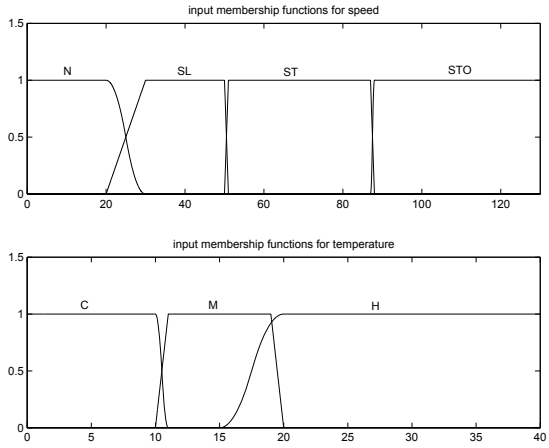


Figure 5 Input Membership Functions

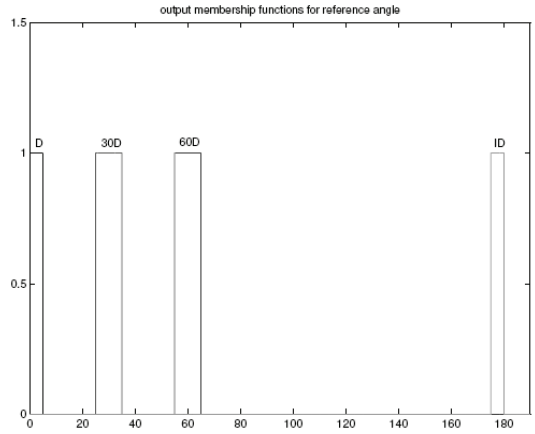


Figure 6 Output Membership Functions

The output of the controller can be expressed as

$$O_o = \frac{\sum_m (O_m \cdot a_{Cm} \cdot b_{Cm})}{\sum_m (O_m \cdot b_{Cm})} \quad (1)$$

Where a_{Cm} and b_{Cm} are the centers and widths of the output fuzzy sets, respectively, for $m = 1,\ldots,4$. The values of b_{Cm} were chosen to be unity. This scaled output corresponds to the control signal (reference angle) to be applied to maintain the position of windcatcher at a desired angle. Fig. 7 represents the normalized output O_o of the proposed fuzzy controller structure as a function of the speed of wind and the temperature. Clearly, it illustrates the nonlinear characteristics of the proposed fuzzy controller structure.

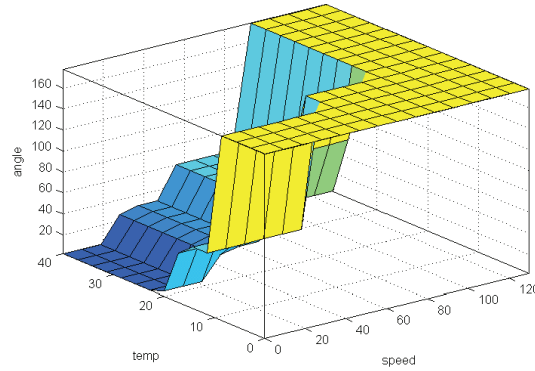


Figure 7 Fuzzy Control Surface

4. SIMULATION

To ensure that this windcatcher can be effective in any condition we had test it through 12 different conditions according to three state of temperature(hot, moderate and cold) and four state of wind's speed (Normal, slight, strong and stormy).Test conditions was simulated in MATLAB. Test results illustrates that the proposed fuzzy logic controller structure can provide considerable control performance over a wide range of operating conditions. PI controller's performance was also simulated for a test reference signal using MATLAB. The results are shown in Fig. 8.

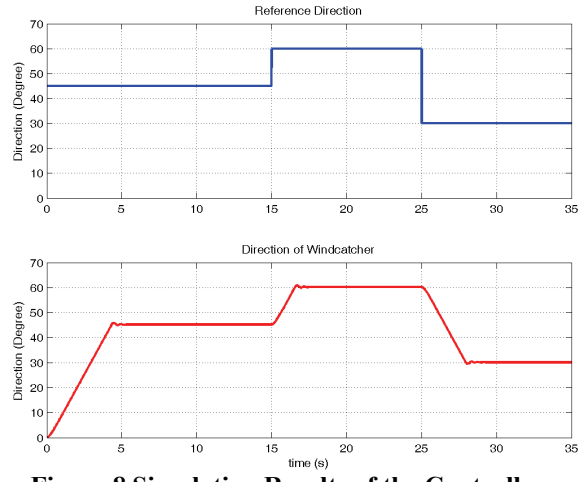


Figure 8 Simulation Results of the Controller

5. CONCLUSION

The main highlights of the proposed design are as follow: at first, Simplicity of the design especially in construction of the mechanical parts. Secondly, not need to costly energy sources alongside with acceptable performance, and thirdly, its low total cost which make it possible to be installed in not developed area. In addition, this system can be installed in remote areas where are far from cross country electrical lines.

As a supplement system one can use a water spray system in the duct. This makes the entered air more pleasant by making it cool and humid. However in this case, we should use a water supply and additional power supply to run the pumps.

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DESIGN AND DEVELOPMENT OF AN ACTIVE CONTROLLED WINDOW WITH HIGH SOUND TRANSMISSION LOSS

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ABSTRACT

Improving the sound transmission loss (STL) of glazed facades is needed, as required by the 89/106/CEE European Directive, which imposes high STL values for building facades, whose weak part is generally constituted by the presence of windows, sometimes making them not adequate to observe the recently enacted requirements. As passive means (e.g. double windows and laminated glazing) were shown to be effective for increasing STL levels only in the medium-high frequency range of sound waves, in this paper an active control system for the coverage of a lower set of frequencies is experimented, where traffic and railway noise produces high levels of disturbance. This paper investigates the ASAC control system as applied on an experimental active control window prototype, focusing mainly on a dedicated technology that is able to improve its STL in the low frequency range, whose effectiveness has been shown by both Finite Element analyses and experiments.

KEY WORDS

ASAC System, Sound Transmission Loss, PZT Actuators, Finite Element Analysis.

1. INTRODUCTION

The 89/106/CEE European Directive, has made protection against noise a compulsory requirement for buildings. In fact, glazed facades often represent the main problem, as they can respect the strict limits imposed by national regulations only when using expensive solutions. The two main types of passive means for improving STL presently known are laminated glass technology and double glazing, but those methods do not work in the low frequency range: double glazing improve STL in the middle frequency range, while laminated glass panels are useful just to shift the coincidence effect towards higher frequencies [1]. As it can be deduced from the standard UNI 12354:2000, the overall sound reduction index for a generic wall depends on the sound reduction indices of the elements it is made up of and from flanking transmission paths. The first components for a generic façade is given by the insulation of windows and the insulation of opaque elements. It is possible to show [1] that the presence of windows make the opaque part ineffective in improving the overall sound reduction index above a certain point. In other words, windows are too weak in comparison with the opaque part and act as a preferred path for sound transmission. Therefore, the overall sound reduction index should be improved by enhancing the acoustic performances of windows, that are extremely weak in the range of frequencies close to resonances. Hence it is necessary to adopt active technologies that can enhance acoustic performances of windows in the low frequency range, where their resonance frequencies fall. Ref. [2] presents a full description of all the active approaches presently available, whose basic subdivision states between: Active Noise Control (ANC) and Active Structural Acoustic Control (ASAC). The authors have already explained in other contributions [1,3] that the first is not suitable for the purpose of

improving windows' STL because it is based on the production of a cancelling wave that interferes destructively with the disturbing one: it means that some loudspeakers and microphones need to be installed in the receiving environment, and that their functioning should change according to the room shape and to the presence of people, that is clearly not feasible. For that reason the ASAC one was adopted for controlling glazed facades, which is performed by changing the vibration field of structures radiating noise. In this paper it will be shown that ASAC is really effective for sound reduction as both Finite Element simulations and experiments validated such a technology for glazed panels.

2. THE TESTED TECHNOLOGY FOR ASAC CONTROL

2.1 Overview of the Whole Control System

As anticipated in the introduction, the ASAC is suitable because both sensors and actuators are placed on the vibrating glass panels and decrease the noise source's intensity. In Ref. [4] piezoelectric patch actuators were shown to produce control actions not strong enough for glass panels (which has rather high stiffness). Instead piezoelectric stack actuators (PZT) are the best approach for this purpose [5], because they can provide high forces with very low displacements. In Ref. [3] it was shown also that 1 or 2 actuators are enough to properly control acoustic vibrations of glass: preliminary simulations showed that, according to the theoretical behavior of windows subject to acoustic excitations and controlled by one or two point forces, it is possible to reduce noise re-irradiation up to 15 dB. However in that case the real behavior of controlling actuators was approximated with point forces, neglecting further disturbances to glass panels, due to the stiffening structure they need work. When an electric field is sent to actuators like the ones depicted in Fig. 1, they undergo an elongation which transfers an impulse to the glass only in case they are stiffened on the other side. Such a stiffening structure interferes with the dynamic behavior of glass, which must be taken into account when forecasting the expected acoustic improvements provided by the ASAC system.

In the general case, ASAC control systems are characterized by the positioning of actuators and control sensors directly on the controlled vibrating source: they are fixed on glass panels to reduce glass vibrations and the radiated noise as a consequence.



Figure 1 Some Marketed PZT Stack Actuators

There are two types of ASAC control. The first is of feed-forward type, which requires for prior knowledge of disturbance through the use of a reference microphone: in the case of buildings this seems impractical, because it would require the installation of a microphone on the exterior of windows, which is not feasible for functional and esthetic issues. The second is the feedback type (Fig. 2): sensors are positioned on the vibrating surface to detect disturbance coming from the exterior thanks to the use of electronic filters, which analyze those signals and check the vibration induced by the noise; then actuators are switched and the controller separates the vibration induced by the disturbance from the action of PZT stack actuators: at this phase sensors acquire error signals, allowing the controller to compute the optimum voltage to be supplied to actuators in order to reduce the re-irradiated noise towards the interior. Control signals are sent by one amplifier, which converts the inputs from the controller into corresponding voltages for actuators.

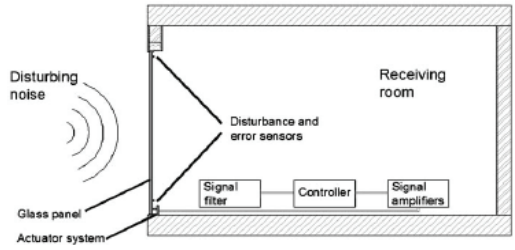


Figure 2 Feedback ASAC Control System

2.2 Design of the Control Strategy

It is shared that when many inputs and outputs are used in the control algorithm, the state space mathematical formulation is advisable [6]. It is used to simplify the equations of vibrational behavior for a glass layer [5]:

$$\ddot{\xi}_{mn} + 2\omega_n \dot{\xi}_{mn} + \omega_n^2 \xi_{mn} = \sum_{i=1}^{L} q_{mn}^i \qquad (1)$$

into a set of first order differential equations, where both vibrations and re-irradiated sound is computed:

$$\begin{aligned} \dot{k} &= A_G \cdot k + B_G \cdot \dot{\xi} \\ y &= C_G \cdot \dot{k} + D_G \cdot \dot{\xi} \end{aligned} \qquad (2)$$

where eq. (2-a) is devoted to the description of the plate vibration field (k), which is dependent to the system's input (ξ); eq. (2) gives back radiated sound (y), which is the final output of the whole system's functioning. The use of first order linear equation simplifies all the mathematical formulation, without renouncing to a thoughtful description of the system behavior. However we should consider that the radiating behavior of windows cannot be completely described by the use of radiation filters, as the state space approach would require. Hence we would suggest in our paper to use an integrated system where state space and finite Element simulations are used at the same time. We would like to make an integrated approach, where two mathematic features are used: at every iteration, state space computations are used to minimize the chosen cost-function, whose inputs are provided by the outcomes of the dynamic and acoustic analysis carried on by the Finite Element software program LMS VirtuaLab Acoustics™.

The main advantage of the integration of these two instruments is given by the ability of the second kind of calculation to produce reliable results, even when complex configurations of actuators fixed on glass panels are experimented. These reliable and accurate results are then exploited for the computation of the optimum control, required to minimize acoustic efficiency of the noise source structure, whose procedures are analytically rigorous and, as can be read in Refs. [5, 7], are generally based on the minimization of a cost function.

2.3 Proposal of One Technology for Controlling Buildings' Windows

The PZT stack actuators in Fig. 1 undergo a strain proportional to the voltage difference provided at their extremes. In order to transfer a certain amount of force to the surface on which they are applied, they need a stiffening structure on the other extreme point, whose role can be explained as depicted in Fig. 3: a stiffening contrast on the actuator.

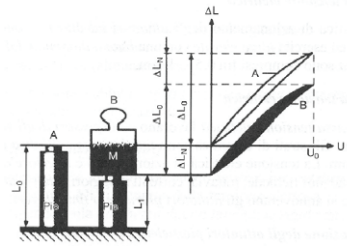


Figure 3 Force Transducer by PZT actuators to Plane Surfaces

In actual use, this system could be realized in a number of different ways: for instance actuators could be inserted between a stiffening structure bonded on the glass plate or on the fixed frame of the controlled window [1]. All the experiments described in the following chapters have been performed by stiffening the actuators through the use of one mass like in Fig. 4, because it is thought to be representative of the general solution for the final actuator, where it is required to produce control point forces.

3. DYNAMIC BEHAVIOR OF ACTIVE CONTROLLED WINDOWS

Both experiments and Finite Element Analyses have been performed on an actively controlled window prototype, where one stack actuator has been installed according to the configuration depicted in Fig. 3. The main aim of the experiments was to validate the model that will be used in the following paragraph to estimate the acoustic improvements which can be provided by such a system.



Figure 4 Experimental Set Up

The experimental set up (Figure 4) used for experiments was made up of one acquisition and control system, and the prototype of window: a rectangular window prototype (1.4x1.0) m wide and 0.006 m thick was built. Arranging a uniform tightening of the glass panel all along the border lines allowed to simulate a simply supporting constraint, by fixing the glass between four cylindrical Teflon made bars with a diameter of 0.01 m on the glass and other four bars under the glass. Two bars were 1.4 m long and other two where 1.0 m long to assure the presence of the constraint all along the perimeter of the prototype. An aluminum metal frame with a rectangular (0.13x0.05) m cross section (ALUSIC type produced by Sicomat s.a.s) was used to provide a uniform contact between glass and Teflon. Four equally spaced cap screws on the shorter side were screwed for the stability of the whole system, and subject to a uniform torque of 0.1 N·m. On the glass one actuator was installed, stiffened through the use of a 96.36 g mass (Fig. 5).

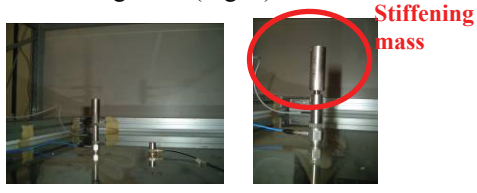


Figure 5 Installation of the Stack Actuator

The first step required the execution of a modal analysis (while the PZT stack actuator was switched off). The experimental set up was made of an instrumented hammer for exciting the structure, one accelerometer connected to a signal amplifier, one PXI™ (distributed by National Instrument) acquisition system, equipped with Labview™ software program for data elaboration.

A grid of points has been drawn on the glass, where measures would have been acquired through the accelerometer. At each measure the PXI acquisition system has recorded data relative to both force generation by the instrumented hammer and vibration generation on each of the points on the grid. At every excitation the accelerometer has been moved from on point of the grid to another. From the acquired data about vibration analyses it is then possible to compute the Response Frequency Function of the glass, and then the modes of the glass have been determined. Table 1 shows the very low shifts between experimental and numerical results.

Table 1 Experimental and Numerical Modal Analysis

MODI m,n	lastra + attuatore	lastra	ERRORE ASS.	ERRORE %
1,1	25.5	25.50	0.00	0
2,1	47	47.50	0.50	1.05
1,2	66.5	67.00	0.50	0.75
3,1	85	85.50	0.50	0.58
2,2	89	89.00	0.00	0.00
3,2	116.5	129.50	13.00	10.04
4,1	133.5	134.50	1.00	0.74
1,3	141	141.00	0.00	0.00
Non definito	164.5	166.5	2.00	1.20
4,2	181	181.50	0.50	0.28
Non definito	187.5			
4,1	200	201	1.00	0.50
3,3	204	203.5	0.50	0.25
4,2	245.5	245.5	0.00	0.00

Numerical data have been generated using ANSYS™ software tool. It is able to overcome other available analytical methods [8], because it can take into account the presence of the actuator with its stiffening mass. The glass plate has been modeled as a shell type plate 0.006 m thick, (1.4x1.0) m wide, with a Young modulus of 6.9x10 MPa, density of 2450 kg/m^3, Poisson coefficient of 0.33. The optimum mesh size was chosen as a squared type element with a 0.02 m side, after an iterative refinement starting from elements with a side size of 0.05 m. Before performing the modal analysis an element simulating the actual actuator has been added on the glass: one steel parallelepiped shaped volume with a 0.02 m long side, Young modulus of 2.5x10^5 MPa, Poisson coefficient of 0.33 and density equals to 22158 kg/m^3. The small shifts between experimental and numerical results (on the average 1.5%) show the validity of this model.

As second validation it was decided to compare the window prototype's dynamic behavior, when excited by point forces comparable with the one which can be provided by the actuator at low

frequencies. The same experimental set up for signal acquisition as before has been used during the experiments, but with a different apparatus for signal generation: in Fig, 6 the actuator with its signal amplifier is photographed in case *a* (purchased by PHISIK INSTRUMENTE), such as the load cell for force monitoring in case *b* (by PCB). All the data have been recorded by a 14 bit National Instruments acquisition board of case *c*. In Fig. 7 we can see the glass plate vibration when excited by the actuator's 0.17 N force at 80.8 and 141.6 Hz respectively. First of all the necessary voltages to produce a 0.17 N point force have been analyzed; then the vibration behavior generated by such a force on the glass has been monitored.

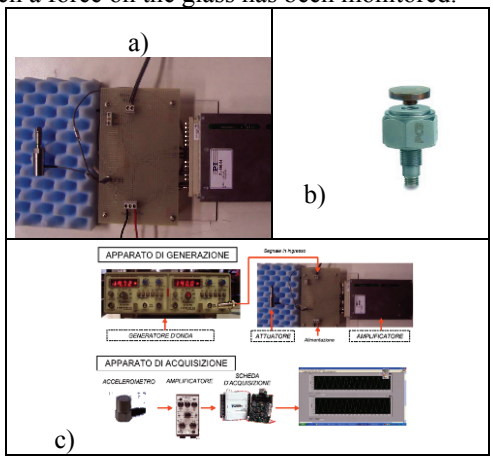


Figure 6 Set Up for Generation of Control Forces

In Figure 7 we can appreciate the practical agreement between numerical and experimental measures.

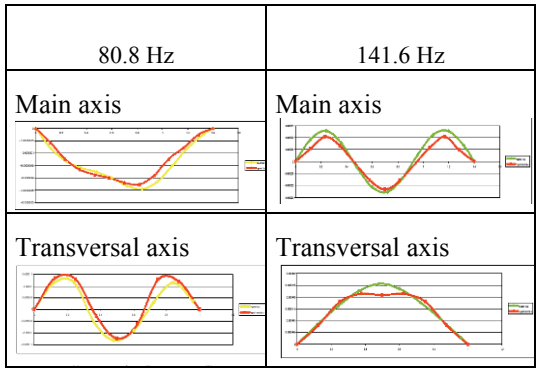


Figure 7 Numerical & Experimental Vibration Analysis

4. ACOUSTIC IMPROVEMENT DUE TO PZT CONTROL SYSTEM

Once that a numerical model for simulating the acoustic behavior of actively controlled windows has been validated, it can be used to infer acoustic improvements that can be brought by such a technologic solution. This estimation has been pursued by comparing noise levels monitored for two different conditions:

1. Free field irradiation,
2. Irradiation into a reverberating room,

When windows are: a) Standard (no control);

b) Actively controlled through ASAC.

All the simulations have been carried out in the case of disturbing noise emitted at the resonance frequency of 140 Hz, because a parametric study has shown it to be the most efficient mode in the low frequency range. Its intensity has been chosen according to the one which can be emitted by a lorry in the nearby (about 2 m far) passing at an average speed (70 km/h) [9]. Conditions 1-a and 1-b have been simulated by assuming that noise is re-irradiated into an anechoic room (enclosed by totally absorbing walls) (1x1x1.4) m large. The model has been implemented in the VirtuaLab^{TM} software, through two steps: first it has been verified that the dynamic behavior of the plate subject to every load condition was the same as the ones computed by the validated ANSYS^{TM} model. Then the vibration tool of the software has been used together with the acoustic tool, in order to infer its performances. In Fig. 8-a we can appreciate free-field noise re-irradiation in the non controlled case, while Fig. 8-b is referred to the controlled case: the highest noise level drops from 62.4 to 49.4 dB (with a 13 dB decrease). A bit, but not too much, different is the situation for the reverberating room in Fig. 9. It is supposed that noise is re-irradiated inside a (2.4 x 2.5 x 2.8) m large room, with the following characteristics: ceiling acoustic impedance was assumed equals to 650-6000i kg/(m^2·s), the wall surrounding the window acoustic impedance equals to 10000-1000i kg/(m^2·s), for the other walls 7700000-100i kg/(m^2·s), and the floor perfectly reflecting. In this case we have a reduction of 9.3 dB, and in the

right framed part of each figure it is shown that at a 1m distance from the irradiating window, the maximum noise level is reduced of 10.1 dB.

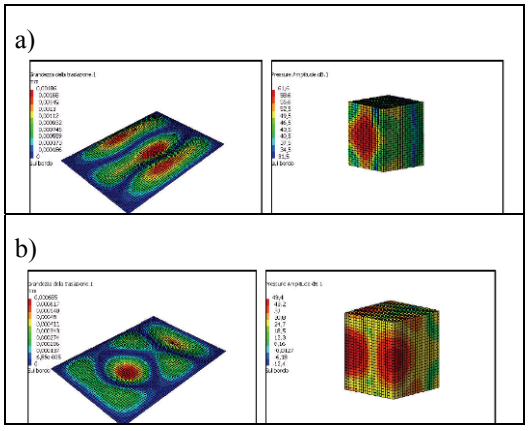


Figure 8 Free-Field Noise Reduction Due to the Use of ASAC Control

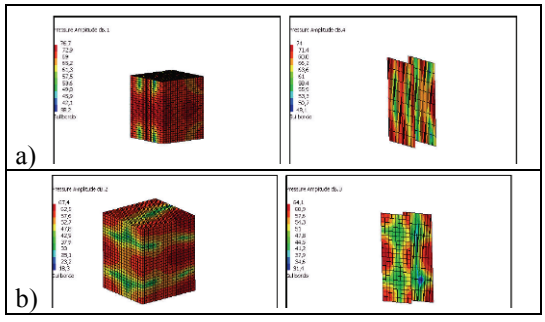


Figure 9 Noise Reduction Due to the Use of ASAC Control Inside a Reverberating Room

5. CONCLUSIONS AND FUTURE RESEARCH

It is straightforward to conclude the big step forward that can be represented by ASAC. Moreover, this research step has been made more reliable, because simulation were conducted taking into account the real properties of the technology used for vibration control (PZT actuator plus its stiffening structure), which modifies the theoretical behavior that would be attributable to glass panes subject to merely point forces (as assumed by analytic models). So far we can conclude that the presence of the stiffness on the PZT stack actuator does not compromise its effectiveness. Other surveys about different technologies will be made, analyzing how they perform throughout the whole noise spectrum.

6. ACKNOWLEDGMENTS

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A 3-DIMENSIONAL FORCE FIELD METHOD FOR ROBOT COLLISION AVOIDANCE IN COMPLEX ENVIRONMENTS

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ABSTRACT

This paper proposes a three-dimensional force field (3D-F^2) method for efficient motion planning and collision avoidance of a 6DOF manipulator in complex and dynamic environments while keeping the planned end-effector's path and speed unchanged. The 3D-F^2 is defined as ellipsoid shapes covering selected links of a manipulator. When the manipulator moves and its ellipsoid force field approaches to an obstacle in a tolerant range, a repulsive force will be generated and considered in the robot kinematic and dynamic analyses. In infrastructure maintenance, spray-painting and sand-blasting operations require that the operating spot "moves" smoothly and continuously along planned path on a work surface at a constant speed, and allow changes in length and orientation of the spray/blasting stream. Thus, the stream is supposed to be another link and the end of stream performs as a spherical joint fixed on the target surface. Various simulations in a construction area show that the 3D-F^2 can retain the operating path and effectively avoid potential collisions.

KEYWORDS

Force Field, 3D-F^2, Collision Avoidance

1. INTRODUCTION

This paper addresses the motion planning and collision avoidance problem for a robot arm in complex environments. Path/motion planning includes off-line and real-time path planning that generates paths automatically for a robot arm to move from one position to another. When planned paths are executed by a robot arm, the robot control system needs to generate a collision-free trajectory and drive every joint of the robot safely and smoothly. Collision avoidance for a whole robot manipulator has been considered as a very important issue, especially in complex and dynamic environments. Distance measuring is a procedure, before collision avoidance, to determine the possibility of collisions. As computing the distance from a manipulator to obstacles using accurate topology is very time consuming, many researchers have been trying to find efficient approaches to speed up the calculation, for example, covering the links of a robot manipulator with polytope, polyhedron [5], [6], sphere [7], [8], [10], [11], ellipsoid, etc., which can significantly reduce computing time. Based on the measured distance between the robot arm and obstacles in the environment, collision avoidance algorithms are then used to steer the movement of a robot arm away from obstacles while fulfilling its task. Many techniques for this objective, for example the Configuration Space (C-Space) method [2], [3], potential field approach [4], [9] and force field method [11], [12], have been developed.

Path/motion planning and collision avoidance have been extensively investigated. Biegelbauer et al. generalised the painting path planning process [1], which is capable of generating collision-free trajectory for the end-effector. Lozano-Perez presented approaches to distance measuring

between polyhedrons which are used for path planning in discrete C-space [2], [3]. Khatib applied the potential field concept for real-time obstacle avoidance for manipulators and mobile robots [4]. Juang applied polyhedrons to represent a manipulator and potential field method to dynamically control manipulators [5], [6]. Greenspan and Burtnyk modelled a robot arm and obstacles with sets of spheres, measured the distances with a weighted voxel map and demonstrated successful collision avoidance and on-line path planning [7], [8]. Lin and Chuang used potential fields in 3-D workspace to generate a collision free path by locally adjusting the robot configuration for minimum potential [9]. Brock and Khatib presented elastic strip framework generating an obstacle bended free space tunnel for a robot to move from point to point [10]. Xie et al. used spheres covering a robot and converted the repulsive forces to joint torques to find the collision free trajectory [11]. D.Wang et al. presented a variable speed force field (VSF^2) method in 2D for multi-mobile robot collaboration and collision avoidance [12]. A relationship between speed and repulsive force is defined to reduce the oscillation in robot speed and orientation.

In operations such spray-painting, the end-effecter of a manipulator is required to move at constant speed along pre-planned path while considering the collision avoidance of the whole robot arm. Collision avoidance for the whole body of a robot arm has not been extensively studied. We propose a 3D-F^2 method in this research. The definition of ellipsoidal three-dimensional Force Field (3D-F^2) covering the links of a manipulator are introduced in Section 2. Section 3 presents a robot model and the approach using 3D-F^2 to fulfil a task. Simulations carried out in a maintenance environment shows that the 3D-F^2 effectively protects the manipulator from possible collisions with obstacles in a complex environment. The remarkable computing time shows that the 3D-F^2 method can be used in real-time applications.

2. DEFINITION OF THE 3D-F^2

This section introduces the definition of the 3D-F^2. To determine the ellipsoid covering a link of manipulator, two points on a link are selected as the foci of the resulted ellipsoid (P_1 and P_2 in Fig. 1). Transformations from the robot joint coordinate system to the global system are given by transfer function ($^i\mathbf{T}_j$) and rotation-translation metrics ($^i\mathbf{A}_j$). $\mathbf{P}_{i(u,v,w)}$ and $\mathbf{P}_{i(x,y,z)}$ are points on the robot's coordinate system and the global system, respectively.

$$ {}^0\mathbf{T}_{n^{th}} = \prod_{m=0}^{n^{th}-1} {}^m\mathbf{A}_{m+1} \tag{1} $$

$$ \mathbf{P}_{i(x,y,z)} = {}^0\mathbf{T}_{n^{th}}\,\mathbf{P}_{i(u,v,w)} \quad ; \text{where } i = (1,2) \tag{2} $$

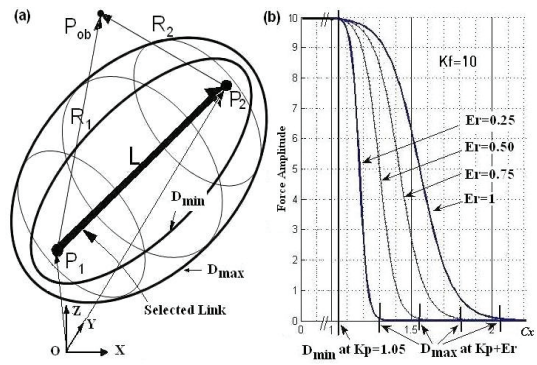


Figure 1 (a) Factors of 3D-F^2 (b) Amplitude of Repulsive Force Between D_{min} and D_{max}

The equations of D_{min} and D_{max} ellipsoids are given in (3) and (4). To ensure that this D_{min} ellipsoid will cover the whole body of the link, the length of the major axis is set to be equal to L*K_p, where L is the distance between the foci and K_p is a constant larger than 1. For any point in the 3D space (P_{ob} in Fig. 1), if the sum of distances, R_1 and R_2, between this point to the foci is equal to the length of the major axis, that is, L*K_p, this point is on the D_{min} ellipsoid. If R_1+R_2 is smaller than L*K_p, this point is inside D_{min}. On the contrary, when R_1+R_2 is larger than L*K_p, the point is outside D_{min} (see Fig. 1). To take the linear speed of the end-effecter into account, we introduce a new factor, E_r, which is the ratio of the instant speed (V_i) and the maximum speed (V_{max}), so E_r is between 0 to1. The length of major axis of D_{max} is set to be L*(K_p+E_r).

$$ \mathbf{L} * K_p = \left|\vec{\mathbf{R}}_1\right| + \left|\vec{\mathbf{R}}_2\right| \tag{3} $$

$$ \mathbf{L} * (K_p + Er) = \left|\vec{\mathbf{R}}_1\right| + \left|\vec{\mathbf{R}}_2\right| \tag{4} $$

$$ E_r = \frac{V_i}{V_{max}} \tag{5} $$

From (3) and (4), if we define *Cx*, is a ratio between $\mathbf{R}_1$+$\mathbf{R}_2$ and **L**, the K_p and K_p+*Er* will

indicate if $\mathbf{P}_{ob}$ is inside or between or outside the D_{min} ellipsoid and the D_{max} ellipsoid.

$$Cx = \frac{|\vec{\mathbf{R}}_1| + |\vec{\mathbf{R}}_2|}{|\mathbf{L}|} \tag{6}$$

Then, the amplitude of repulsive force is given by

$$|\vec{\mathbf{F}}_{rep}| = Kf - \left(\frac{Kf}{1 + e^{\left(-\frac{10\,(Cx - Kp - 0.5\,Er)}{Er} \right)}} \right) \tag{7}$$

Kf is maximum repulsive force. Fig 1b shows how the repulsive force varies with E_r and the position between D_{min} and D_{max}. This definition ensures the smooth change of the force. The direction of the repulsive force is defined to be the unit vector that points from $\mathbf{P}_{ob}$ to $\mathbf{P}_1$ or $-R_1$.

$$\vec{\mathbf{F}}_{rep} = \frac{\vec{\mathbf{P}}_1 - \vec{\mathbf{P}}_{ob}}{|\vec{\mathbf{P}}_1 - \vec{\mathbf{P}}_{ob}|} * |\vec{\mathbf{F}}_{rep}| \tag{8}$$

3. KINEMATICS AND DYNAMICS

In the section, we analysis the manipulator's kinematics and dynamics in operations such as spray-painting and then introduce how the 3D-F^2 method can be applied for planning and collision avoidance.

3.1 Model of Robot

In a spraying operation, the end effector of the manipulator needs to follow a pre-planned path and move continuously. To maintain the target point, the manipulator model has to be adapted by assuming a virtual link from the robot end-effecter to the target point and a virtual joint at the spraying spot which contains three rotating axes ($R_{z,\psi}R_{y,\varsigma}R_{x,\rho}$). Thus, the model of the robot arm can be represented in Figure 2. This modified model has two fixed pivots at both ends of a serial chain-link. The stream pivot is an instant point that moves along a pre-planned path.

3.2 The Effects of Repulsive Force

When an obstacle or any part of an obstacle is inside of the D_{max} ellipsoid of the virtual stream link, a repulsive force will be generated on a point that has the smallest *Cx* and has maximum repulsive force. Moment ($\vec{\mathbf{M}}_{1,\psi,\varsigma,\rho}$), which is a cross product of the distance vector of stream direction ($\vec{\mathbf{l}}_{\text{stream link}}$) and the force ($\vec{\mathbf{F}}_1$), is defined by (11) and will change the stream direction. The repulsive force at the lower arm ($\vec{\mathbf{F}}_2$) is defined from the nearest point of an obstacle and is toward to the end of lower arm at $\mathbf{P}_{1,2}$.

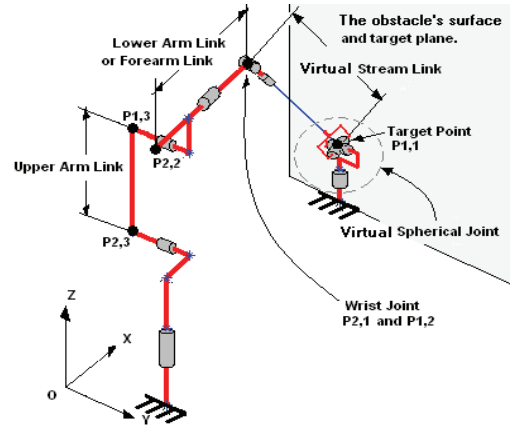


Figure 2 The Stream Link, Virtual Spherical Joint and Points of the Robot Arm

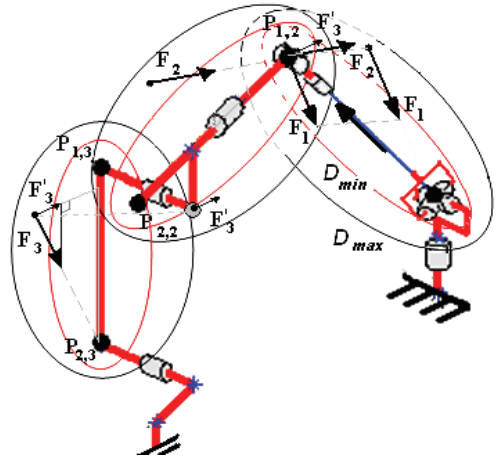


Figure 3 Repulsive Forces on the Links of a Robot Arm

$$\vec{\mathbf{M}}_{1,\psi,\varsigma,\rho} = \begin{bmatrix} M_{1,\psi} \\ M_{1,\varsigma} \\ M_{1,\rho} \end{bmatrix} = \vec{\mathbf{l}}_{\text{stream link}} \times \vec{\mathbf{F}}_1 \tag{9}$$

As shown in Figure 3, $\vec{\mathbf{F}}_2$ is going to change the stream link direction by pushing or pulling the wrist of the robot arm. In a different way, the repulsive force of the upper arm ($\vec{\mathbf{F}}_3$) is divided into two perpendicular vectors, one points to the upper arm link at $P_{2,3}$ the shoulder joint and another ($\vec{\mathbf{F}}_3'$) to its perpendicular plane. The force would have

an effect to the rotation of shoulder indirectly because it could make the robot missing the target. While the force $\vec{F}_3'$ is pushing the elbow of the robot, there is a reaction against the force. With this force, the forearm transfers the $\vec{F}_3'$ in parallel along itself to push the stream as well as the repulsive force from lower arm.

$$\vec{\mathbf{M}}_{2,\psi,\varsigma,\rho} = \vec{\mathbf{l}}_{\text{stream link}} \times \vec{\mathbf{F}}_2 \tag{10}$$

$$\vec{\mathbf{M}}_{3,\psi,\varsigma,\rho} = \vec{\mathbf{l}}_{\text{streamlink}} \times \vec{\mathbf{F}}_3' \tag{11}$$

$$\vec{\mathbf{M}}_{rep\ \psi,\varsigma,\rho} = \sum_{i=1}^{3} \vec{\mathbf{M}}_{i,\psi,\varsigma,\rho} \tag{12}$$

If there are no obstacles, repulsive forces become zero, the end-effecter of the robot end-effecter has to return to the planned orientation as the result of a virtual torque $\vec{\mathbf{M}}_{sp,\psi,\varsigma,\rho}$ defined by (13). $\mathbf{T}_{\psi,\varsigma,\rho}$ and $\mathbf{A}_{\psi,\varsigma,\rho}$ are the planned orientation and the actual orientation of the end-effecter, respectively, and *Ksp* is a virtual spring constant.

$$\vec{\mathbf{M}}_{sp,\psi,\varsigma,\rho} = Ksp*(\mathbf{A}_{\psi,\varsigma,\rho} - \mathbf{T}_{\psi,\varsigma,\rho}) \tag{13}$$

Thus the torques are applied to the robot arm will be given by

$$\vec{\mathbf{M}}_{\psi,\varsigma,\rho} = \begin{cases} \vec{\mathbf{M}}_{rep_{\psi,\varsigma,\rho}} & ;\text{one of } \mathbf{F}_{i,\text{rep}} > 0 \\ \vec{\mathbf{M}}_{sp_{\psi,\varsigma,\rho}} & ;\text{all of } \mathbf{F}_{i,\text{rep}} = 0 \end{cases} \tag{14}$$

3.3 Inverse Kinematics and Dynamics

The dynamics of the stream link can be described with spatial motion equations (16-18). Parameters in the equations include target position ($\mathbf{S}_t$), start position ($\mathbf{S}_s$), current position ($\mathbf{S}_c$), previous position ($\mathbf{S}_p$), speed (v_p), differential time (dt), direction of the path ($\mathbf{D}$), current orientation ($\mathbf{O}_c$), previous orientation ($\mathbf{O}_p$) and the mass property of the virtual stream link (*Km*).

$$\mathbf{D} = \frac{\mathbf{S}_t - \mathbf{S}_s}{\|\mathbf{S}_t - \mathbf{S}_s\|} \tag{15}$$

$$\mathbf{V} = v_p*\mathbf{D} \tag{16}$$

$$\mathbf{S}_c = \mathbf{S}_p + \mathbf{V}*dt \tag{17}$$

$$\mathbf{O}_c = \mathbf{O}_p + Km*0.5*\vec{\mathbf{M}}_{\psi,\varsigma,\rho}*dt^2 \tag{18}$$

The poses of the manipulator joints, [$\mathbf{\Theta}$], can be obtained from the position and orientation in the Cartesian space [x y z ψ ζ ρ] by applying inverse kinematics (IK):

$$[\mathbf{\Theta}] = \boldsymbol{IK}\ (\ [\mathbf{S}_c\ \ \mathbf{O}_c], [\mathbf{\Theta}_{\text{previous}}]\ ) \tag{19}$$

[$\mathbf{\Theta}_{\text{previous}}$] is the joint poses in the previous step, which is used in pose selection to reduce jerk in joint movement. The angles of the first three joints, shoulder to elbow, come from the coordinate of the wrist joint ($\mathbf{P}_{2,1\ \text{current}}$) from (20). Input the first three joints' angles, Θ_1, Θ_2, Θ_3 to ${}^0\mathbf{T}_6$ to work out ${}^3\mathbf{T}_6$ in term of [$\mathbf{n'\ s'\ a'}$] in (23) and compare it with ${}^3\mathbf{T}_6$ in (23) from forward function to get $\Theta_4,\Theta_5,\Theta_6$.

$$\begin{bmatrix} \mathbf{P}_{2,1\ current} \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{R}_{z,Oc(\psi)} & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R}_{y,Oc(\varsigma)} & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R}_{x,Oc(\rho)} & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -l_{\text{streamlink}} \\ 1 \end{bmatrix} + \begin{bmatrix} Sc \\ 1 \end{bmatrix} \tag{20}$$

$${}^0\mathbf{T}_3\,{}^3\mathbf{T}_6 = {}^0\mathbf{T}_6 = \mathbf{R}_{z,Oc(\psi)}\mathbf{R}_{y,Oc(\varsigma)}\mathbf{R}_{x,Oc(\rho)} = \begin{bmatrix} n_x & s_x & a_x \\ n_y & s_y & a_y \\ n_z & s_z & a_z \end{bmatrix} \tag{21}$$

$${}^3\mathbf{T}_6 = \frac{{}^0\mathbf{T}_3^{\,T}}{\left|{}^0\mathbf{T}_3\right|} \begin{bmatrix} n_x & s_x & a_x \\ n_y & s_y & a_y \\ n_z & s_z & a_z \end{bmatrix} = \begin{bmatrix} n'_x & s'_x & a'_x \\ n'_y & s'_y & a'_y \\ n'_z & s'_z & a'_z \end{bmatrix} \tag{22}$$

$${}^3\mathbf{T}_6 = {}^3\mathbf{A}_4\,{}^4\mathbf{A}_5\,{}^5\mathbf{A}_6 \tag{23}$$

4. SIMULATION AND RESULTS

Simulations are carried out in an infrastructure maintenance environment. A manipulator mounted on a lift platform is supposed to spray-paint certain area of a maintenance site. The manipulator model in these simulations is Denso 6556 [13]. The simulation program runs on MATLAB7.1 in a Pentium 4 computer with a 2.8GHz CPU and 1GB RAM. The values of parameters in the simulations are set to be v_p = 30 mm/sec, *dt* = 0.1 sec, *Km*=2, K_f=[50 20 20], K_p=[1.01 1.1 1.1], *Er*=[0.025 0.15 0.15] and *Ksp*= 2.

4.1 Case 1

The robot is lifted under a ceiling and spray-paints the surface of the ceiling. Figure 4 shows simulation snapshots of the robot arm with 3D force field, D_{min}, D_{max}, and the end effector's paths. Points 1 to 4 are a pre-planned path denoted by the solid blue line in Fig. 4a. The spray-painting direction is set to be normal to the ceiling surface

in this task. The robot performs a motion that avoids crashing into a flank on the wall and a hanging ventilator beside it. Figure 5 shows the changes of joint angles from point 1 to 4 in Fig 4a. The end-effecter of the manipulator traveled 4600 mm in total in 153 seconds. The computation time required in this simulation is only 63 seconds.

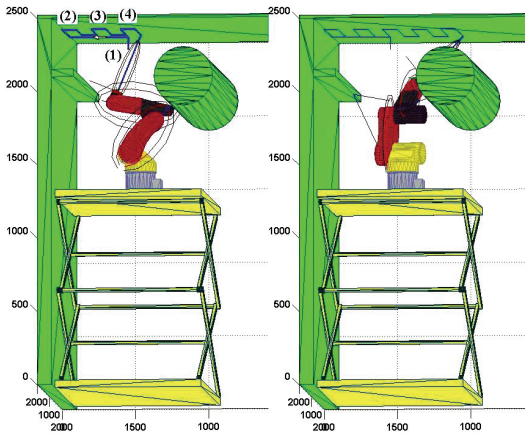


Figure 4 Case1: Ceiling-Spraying Task

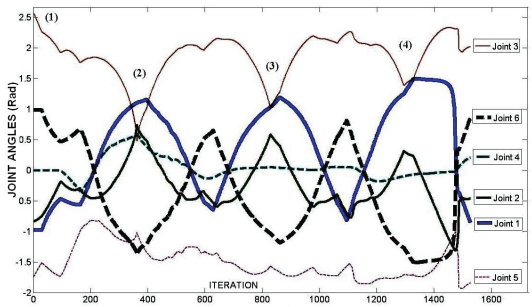


Figure 5 Angles of Joints Along the Path (Case 1)

4.2 Case 2

In this simulation, a vertical wall is painted by the robot (Fig. 6) and the resulted joints' angles are shown in Fig. 7. The path is set upon a vertical side of the wall. The simulation is carried out using the same end-effecter speed and the same force field parameters as those in Case 1, except that stream length is set as 400mm the end-effecter of the manipulator traveled 2750 mm in total in 92 seconds and the computation time required is 46 seconds only.

4.3 Case 3

The robot paints a hanging ventilator (Fig. 9) and joints' angles are shown in Fig. 10. The path is set upon the surface of the cylindrical ventilator. The simulation is carried out using the same end-effecter speed and the same force field parameters as those in Case 1, except that stream length is set as 350mm the end-effecter of manipulator traveled 2300 mm in 77 seconds and the computation time required is 32 seconds.

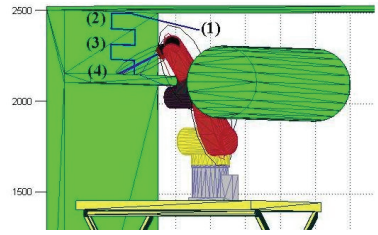


Figure 6 Case2: Wall Spraying Task

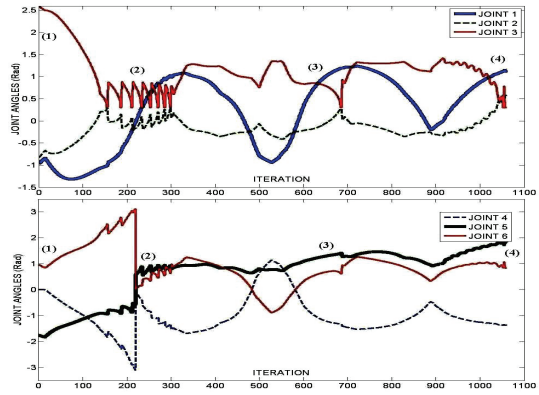


Figure 7 Angles of Joints Along the Path (Case 2)

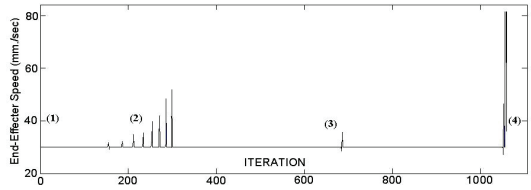


Figure 8 End-Effecter Speed in Case2

4.4 Discussion

The simulation results show that the 3D-F^2 method is able to prevent the robot arm from collisions with obstacles in a complex environment. It also can be seen clearly that the 3D-F^2 method is fast enough to be implemented in the real-time trajectory planning and collision avoidance for manipulators. It can be seen from Fig. 7 and Fig. 10 that the angle changes of some joints are not always smooth although the path is a straight line. Oscillations occur when the robot arm reaches to

some corner areas, such as point 2 in Fig. 6 and point 4 in Fig. 9. In the case of Fig 6, the force field of the stream needs to protect the stream link from obstacles from several directions, i.e. ceiling and wall. The stream link will suffer the repulsive forces from ceiling and wall alternatively, which causes the rapid change of the orientation of stream link and the linear speed of stream link on the working surface (see Fig. 8 and Fig. 11). As a result, the spraying point will fluctuate around the target point. Please note that these fluctuations are instantaneous and only 1 or 2 iterations or 0.1 to 0.2 seconds. They can be easily reduced by applying a damper factor. Besides, there are a few situations that the robot arm reaches its joint limit or workspace limit. These problems will be addressed in our future research work.

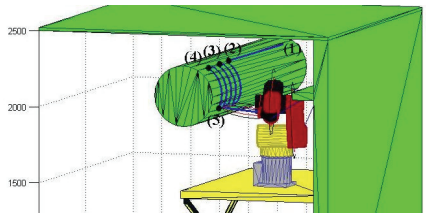


Figure 9 Case3: Ventilator Spraying Task

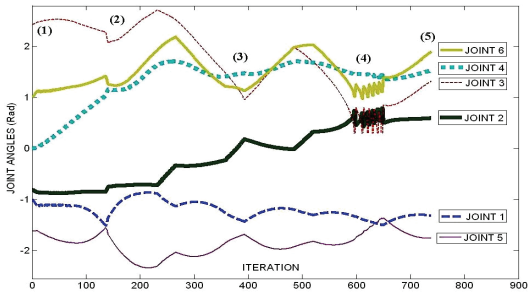


Figure 10 Angles of Joints Along Path (Case3)

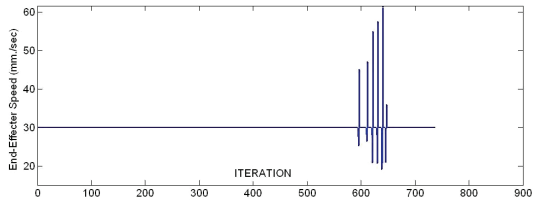


Figure 11 End-Effecter Speed of Case3

5. CONCLUSION AND FUTURE WORK

This paper presented a novel 3D-F^2 method for real-time collision avoidance and motion planning of manipulators in known complex and dynamic environments. With the 3D-F^2, a manipulator is capable of moving its end-effector along a pre-planned path in a constant speed while avoiding obstacles simultaneously. Simulations carried out in a complex environment demonstrate the efficiency and feasibility of the 3D-F^2. In a spray operation, stream length is allowed to change in a certain range, which introduces another degree of freedom. In the next stage of research, the stream link will be represented with a prismatic joint. Further experiments with a real robot in a real working environment will also be conducted.

6. ACKNOWLEDGMENT

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TIME-OPTIMAL CONTROL OF CONSTRUCTION TRANSPORT SYSTEMS WITH SUSPENDED LOADS

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ABSTRACT

The paper describes time-optimal control of construction transport systems with suspended loads, for example gantry type robots. Permissible oscillations of the loads are restricted because of safety requirements while transporting, especially at the end point. A mathematical model of such systems is presented as a pendulum attached by a suspension to a rigid robot body. The time-optimal control consists of transferring the system from an arbitrary initial state to a final state without oscillations of the loads. A control function is velocity of the body. This velocity is bounded. The length of the suspension can be changed while transporting of the load. The optimal motion modes are described. The theoretical switch lines and their approximations are obtained. An implementation of the control system for the start with stopping oscillations, motion without oscillations and the braking with stopping oscillation at the set end point is presented. Simulation results are discussed.

KEYWORDS

Time-optimal Control, Construction Transport System, Suspended Load

1. ANTI-SWAY CONTROL OF SUSPENDED LOADS

Control problems for construction robotic systems with oscillating elements arise in automation of transportation of different suspended construction loads.

Examples of such transportation systems are gantry type robots and robotic cranes. Permissible oscillations of the loads are restricted because of safety requirements while transporting, especially at the end point.

Anti-sway control of suspended loads on shipboard robotic cranes was explored in [1]. Inverse kinematics and sliding mode control approaches were applied in this task. Methods and apparatuses for reducing the oscillatory motion of rotary crane payloads during operator-commanded or computer-controlled maneuvers were investigated in [2]. An input-shaping filter receives input signals from multiple operator input devices and converts them into output signals readable by the crane controller for damping the payload tangential and radial sway associated with rotation of the jib.

In this paper, the time-optimal anti-sway control problem is considered. The developed control system can decrease time and increase effectiveness of transportation. The control takes into account changing of the suspension length during transportation. It implements a three step motion mode: start with stopping oscillations, motion without oscillation and braking with stopping oscillation.

The mathematical model of the considered transport system is shown in Figure 1.

It consists of a suspension with the construction load of mass m. The suspension by length L is attached to a rigid body of the transport system.

The body can move with velocity V along the horizontal axis X.

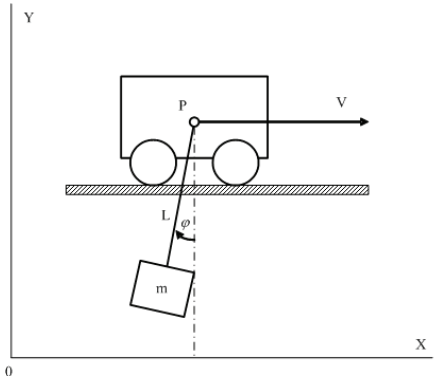


Figure 1 Model of the Transport System

The dynamic equations of the system motion for small oscillations in the vertical plane are given [3] by

$$\ddot{\varphi} + mgL\varphi = mL\omega$$
$$\dot{x} = V$$
$$\dot{V} = \omega \quad , \qquad (1)$$

where x motion coordinate, φ angle of oscillations, g gravity acceleration, ω horizontal acceleration of the suspension point P. The velocity is bounded by the condition

$$-V_{\max} \le V \le V_{\max} \quad , \qquad (2)$$

where Vmax is the maximal possible velocity of the transport system.

The feedback problem of the start with stopping load oscillations and motion without load oscillation is as follow: it is necessary to transfer the system (1), (2) from an arbitrary initial state $\varphi(0)$, $\omega(0)$ to the final state without oscillations within minimum time *T*.

Introducing dimensionless variables [3] and variable

$$\psi = V - \dot{\varphi} \quad ,$$

the motion equations (1) and the anti-sway condition are reduced to the following equations

$$\dot{\psi} = \varphi$$
$$\ddot{\psi} + \psi = V$$
$$\varphi(T) = 0 \qquad (3)$$

The velocity $V(t)$ is the control function which is assumed to be restricted between –1 and +1 that corresponds to the boundary conditions (2). The feedback control $V(\psi, \varphi)$ transferring the system (3) from the arbitrary initial state (ψ^0, φ^0) to the final state of the start mode with stopping oscillations $(V_{max}, 0)$ is build similarly to the feedback control in [3]. The time-optimal control uses maximal value of the velocity forward and back in turn.

The theoretical switch lines and approximations of the implemented switch lines for the start with stopping oscillations, motion without oscillation and braking with stopping oscillation are shown in Figure 2.

The theoretical switch line 1 represents the start with stopping oscillations and motion without oscillation. The implementation of the switch line for the start with stopping oscillations and motion without oscillation is the line 2. The theoretical switch line 3 represents the braking mode with stopping oscillation. It has the final state (0, 0) on the phase plane.

The implementation of the switch line for the braking mode is the line 4.

A phase trajectory 5 of the braking mode for the theoretical system from an initial point (ψ^0, φ^0) is A-B-0. The proposed piece-wise-linear approximation of the switch lines is convenient for the implementation.

Simulation results show that transient time for the experimental switch lines exceeds the transient time for the theoretical switch line by less then 10% for the same initial deviation of the load.

This difference can be reduced if permissible accuracy at the end point of transportation is set by means of a dead zone for the drive system control. It accelerates the process of control also.

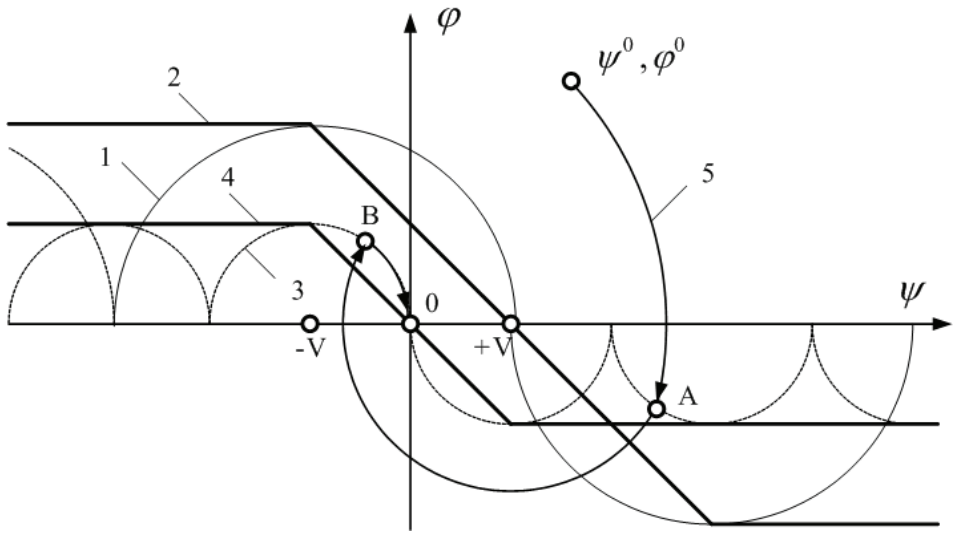


Figure 2 Theoretical Switch Lines and Implementation of the Switch Lines

A scale of the switch lines depends on the suspension length. The scale is corrected for different values of the suspension length. It implements using information from a suspension length sensor.

The correction is carried out by vertical changing of the switch line scale. Horizontal parts of the switch line for the start mode are changing according to the following equation

$$|\varphi| = 2VL^{-\frac{1}{2}}g^{-\frac{1}{2}}$$

Horizontal parts of the switch line for the braking mode are changing according to the following equation

$$|\varphi| = VL^{-\frac{1}{2}}g^{-\frac{1}{2}}.$$

The inclination of the switch lines in the central parts is proportional to the value V_{max}.

2. IMPLEMENTATION OF THE CONTROL SYSTEM

A block diagram of the control system is shown in Figure 3. The object to be controlled is a mobile transport system (TS) with the suspended load. The control parameter is the transport system velocity. It is necessary to control only the sign of the velocity, since its absolute value V_{max} is the same for the stationary regime in both directions for many types of such transport system with the suspended load [4].

The system operates as follows. An angle sensor (AS) generates the signal proportional to the angular velocity of the load oscillations by a differentiator (D). This signal is subtracted from the output signal of a transport system's linear velocity sensor (LVS).

As result, the signal corresponding to the velocity of the load is produced. The linear velocity V of the transport system is used for determination of the covered distance x. This value is formed by an integrator (I). The value x_f is an initial point of the braking mode. It is calculated in advance assuming that the suspension length is not changing while braking and there are no load oscillations at this point [5]. This situation is real because the distance of braking is relatively short and the mode with stopping oscillations is implemented before.

The values of the current coordinate x and the value x_f are compared. If the value

$x_f - x \geq 0$,

then the start with stopping oscillations and motion without oscillation have to be done. If the value

$x_f - x < 0$,

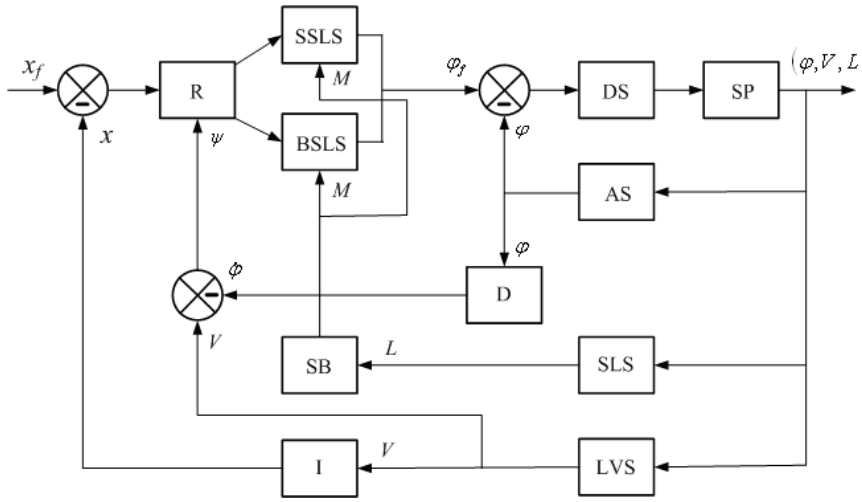


Figure 3 Block Diagram of the Control System

then transition to the braking mode should be produced.

A resulting signal of the comparison goes to a control input of a relay (R). A positive control signal connects an information input of the relay to a start switch line simulator (SSLS) that implements the switch line of the start mode as a function of the load velocity by means of a computational unit. A negative control signal connects an information input of the relay to a brake switch line simulator (BSLS) that implements the switch line of the braking mode.

The scale of the switch lines is corrected for different values of the suspension length by means of signals *M* from the suspension length sensor (SLS) using a scale block (SB).

A value of the corresponding ordinate φ_f of the switch line is generated on a simulator output. This output is compared with a current load angle φ by means of the comparator. If the difference

$$\varphi_f - \varphi \geq 0,$$

the phase point is under the corresponding switch line and control signal is + V_{max}.

If the difference

$$\varphi_f - \varphi < 0,$$

the phase point is over the corresponding switch line and control signal should be $-V_{max}$.

A drive system changes direction of its output velocity according to a sign of the described input control signal. As a result, the system implements anti-sway control for the suspended load transportation taking into account variable suspension length.

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DEVELOPEMENT OF THE GRIPPING CONTROL ALGORITHM FOR WIRE-SUSPENDED OBJECT IN STEEL CONSTRUCTION

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ABSTRACT

Robot system used in building construction sites can efficiently reduce construction time and increase safety by replacing human in dangerous operations. This paper describes the development of a robotic manipulator control algorithm which provides stable and efficient gripping of a pendulum-like object. The pendulum object mimics the construction materials hanging from tower crane, such as steel beam and column. The robot should be able to handle the heavy objects in order to be used in the building construction sites. This control algorithm requires dynamic modeling of the hanging object. To simplify the analysis, the dynamic modeling was limited to the 2 dimensional pendulum movements in x-y plane. In order to achieve the stable and efficient gripping, a shock isolator is designed using a pre-acting control.

KEYWORDS

Robot, Gripping Control, Pre-Acting Control, Shock Isolator, Steel Construction

1. INTRODUCTION

As social problems like aging of population, falling birth rate, etc, have emerged, it becomes necessary that manpower be replaced with automation equipments such as robots. Especially, construction industry has many dangerous factors and needs a lot of manpower. This paper deals with an automation problem that can arise from the assembly of steel structures in high-rise building construction sites.

The assembly process of steel structures includes handling extremely heavy objects, for example, steel beams, columns, girders, etc., which are usually carried by a tower crane installed at construction site. The steel construction also contains fundamental structure of bolting linkage between H-shaped beams (or girders) and H-shaped columns. For the bolting process, human workers generally climb up on a steel structure, place a new beam or column hanging from tower crane in position, and bolt them directly. This process is very dangerous to the workers, and takes long time to bolt down. Furthermore, this assemble process is seriously influenced by weather, such that it can not be carried out during windy or rainy days. It is a fatal weakness to some countries that have long period of rainy days.

In order to automate the process of steel structure, one of essential requirements is the ability to safely grip the H-beam (beam or column) that weighs from 4 tons to 10 tons. The H-beam hanging from tower crane inevitably generates tremendous amount of impact when it swings due to its heavy weight. So, it is necessary to appropriately control the automation equipments (robot manipulators, for example), which isolates the impact and protects the equipments from the shock caused by the huge mass of the H-beam. This paper presents

a strategy to deal with this problem. The strategy contains pre-acting control to protect the manipulator from the shock. It estimates a magnitude of the shock from wire-suspend object by sensor data and generates pre-acting control. If the magnitude of the shock from the hanging beam is under a limit, the pre-acting control is activated and generates control force to opposite side before the impact, so that the robot system can grip the H-beam hanging from tower crane safely.

2. BACKGROUND

2.1 Manipulator Design

Figure1 shows a potential design of the manipulator to grip H-beam. This robot system is connected to another carrier mechanism housed in construction factory (CF). The manipulator can be positioned anywhere by the carrier mechanism.

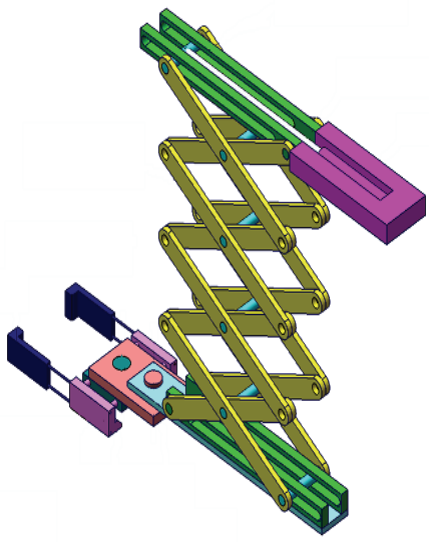


Figure 1 Design of the Manipulator

The manipulator has three degrees of freedom. Among them, one is vertically up and down movement with scissor-jack type joints. The others are the translation in front and backward directions and rotation of the end-effector joint. All actuators are driven by hydraulic systems. There is a space reserved for bolting robot which is used to assemble beams and columns. This manipulator is designed to have a mobility and a capability that can grip the H-beams in all directions.

2.2 Dynamic Model of Pendulum-Like Object

The analysis for the motion of the H-beam hanging from tower crane is performed based on the following assumptions:

1) Pendulum motion of H-beam is restricted to 2-D plane
2) Swing angle is small, 5 degree is chosen as a reference value ($\theta \le 5^{\circ}$)

These assumptions are feasible because the cable from the tower crane is long and main impact acts to the normal direction of end-effector plane.

Figure 2 shows 2-D plane motion of the H-beam hanging from crane. The equation of motion is derived using free-body-diagram shown in Fig. 2 and Lagrange-Newton method. First of all, the velocity and acceleration of the object can be figured out from Figure 2.

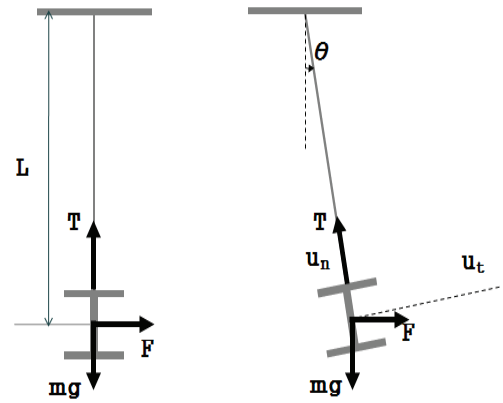


Figure 2 Model of 2-D Plane Motion

$$v = \upsilon_t u_t = l\dot{\theta} u_t \tag{1}$$

$$a = a_t u_t + a_n u_n = l\ddot{\theta} u_t + l\dot{\theta}^2 u_n \tag{2}$$

Also, the kinetic energy, potential energy, and virtual work are found out to apply Lagrange-Newton equation.

$$T = \frac{1}{2} m(\upsilon_t^2 + \upsilon_n^2) = \frac{1}{2} m(l\dot{\theta})^2 \tag{3}$$

$$V = mgl(1 - \cos\theta) \tag{4}$$

$$\overline{\delta W} = F\delta x = F\delta(l\sin\theta) = Fl\cos\theta\delta\theta \tag{5}$$

where,

m : object(beam) mass

l : length of wire

g : gravity acceleration

θ : angular displacement

$\dot{\theta}$: angular velocity

$\ddot{\theta}$: angular acceleration

θ, $\dot{\theta}$, $\ddot{\theta}$ are prescribed functions of time which have sinusoidal form.

And the virtual work is expressed in terms of generalized force and generalized displacement as follow

$$\overline{\delta W} = \Theta\delta\theta \tag{6}$$

Using Eq. (5) and (6),

$$\Theta = Fl\cos\theta \tag{7}$$

$$L = T - V \tag{8}$$

Eq. (3), (4), and (7) are substituted into Eq.(8), the followings are obtained

$$L = \frac{1}{2}m(l\dot{\theta})^2 - mgl(1-\cos\theta) \tag{9}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\theta}}\right) - \frac{\partial L}{\partial\theta} = \Theta \tag{10}$$

Finally, inserting Eq.(7) and (8)

into Eq (9)

$$ml^2\ddot{\theta} + mgl\sin\theta = Fl\cos\theta \tag{11}$$

$$ml\ddot{\theta} + mg\theta = F\cos\theta \tag{12}$$

based on the assumption of small swing angle, such that $\sin\theta \approx \theta$.

$$F = \frac{ml\ddot{\theta} + mg\theta}{\cos\theta} \tag{13}$$

3. CONTROL ALGORITHM

3.1 Pre-Acting Control for Isolator

H-beam has heavy weight ranging from 4 tons to 10 tons but the robot system has light weight under 1 tons and relatively weak due to its structural characteristics.

As such, a shock isolator is required to protect the manipulator from the impact by swinging object. Fig. 3 shows the design concept of the shock isolator. If the magnitude of shock is relatively compared to the strength of the robot arm, the robot system can grip H-beams safely using this isolator.

To design a better isolator, pre-acting control algorithm is used. Using appropriate sensors (camera, for example), the robot system can predict the instant of the shock. Using this data, the control effort is put before the shock is applied and the shock is actively absorbed during the impact.

The problem of limiting performance of shock isolator can be formulated with pre-acting control [3],[4].

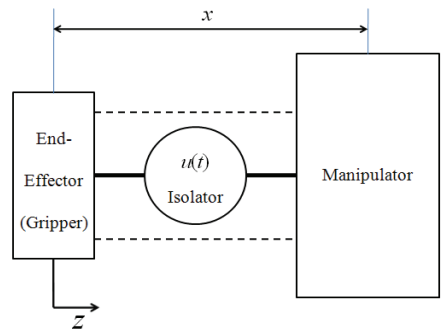


Figure 3 Schematics of Shock Isolator

From Fig. 3, the governing equation can be formulated as,

$$m\ddot{x} + u = -m\ddot{z} \tag{13}$$

where,

m : manipulator mass

x : manipulator displacement relative to end-effector

z : manipulator displacement relative to global frame

u : control force

$\ddot{z}$ is a prescribed function of time and its value is zero during $-t_0 < t < 0$. Its result applies to the initial conditions, which are,

$$x(-t_0) = 0, \quad \dot{x}(-t_0) = 0 \tag{14}$$

It is important to find out pre-acting control $u_0(t)$ defined during $-t_0 < t < \infty$,

$$\min_u \left\{ \max \left| x - x_0 \right| \right\} \quad \text{while} \quad \max_t \left| \ddot{x} \right| \le U \tag{15}$$

$$\max_t \left| \ddot{x} \right| = u_0(t) \tag{16}$$

Where U is defined to minimize the maximum peak absolute value of the relative displacement of the manipulator as Eq. (15) and (16).

Let the shock is instantaneous impact at $t = 0$, then $\ddot{z}(t)$ is expressed by Dirac-Delta function like Eq.(17). That is,

$$\ddot{z}(t) = \ddot{z}_0 \delta(t) \tag{17}$$

Graphical-analytical method is used to solve limiting performance problem. An optimal control force is obtained by assuming unit pre-acting time, $t_0 = 1$ [5]

$$u_0(t) = \begin{cases} -1, & (-1 \le t < -3/4) \\ 1, & (-3/4 \le t < 1/2) \\ 0, & (1/2 \le t \le \infty) \end{cases} \tag{18}$$

Fig. 4 shows the time history of the optimal pre-acting control force by plotting Eq. (18).

From Eq. (17) and (18), Eq. (13) is expressed as

$$m\ddot{x} + u = 0 \tag{19}$$

Subject to the conditions at $t = -t_0$ and $t = 0$

$$x(-t_0) = 0, \quad \dot{x}(-t_0) = 0 \tag{20}$$

$$\dot{x}(-0) + \ddot{z}_0 = \dot{x}(+0) \tag{21}$$

Using Eq. (18) ~ Eq. (21), the velocity and displacement of x during $-t_0 < t < \infty$ can be found, where $m = 1$ and $\ddot{z}_0 = 1$

$$\dot{x}(t) = \begin{cases} t + 1, & (-1 \le t < -3/4) \\ -t - 1/2, & (-3/4 \le t < 0) \\ 1/2 - t, & (0 \le t < 1/2) \\ 0, & (1/2 \le t < \infty) \end{cases} \tag{22}$$

$$x(t) = \begin{cases} (t+1)^2/2, & (-1 \le t < -3/4) \\ 1/16 - (2t+1)^2/8, & (-3/4 \le t < 0) \\ 1/16 - (2t+1)^2/8 + t, & (0 \le t < 1/2) \\ 1/16, & (1/2 \le t < \infty) \end{cases} \tag{23}$$

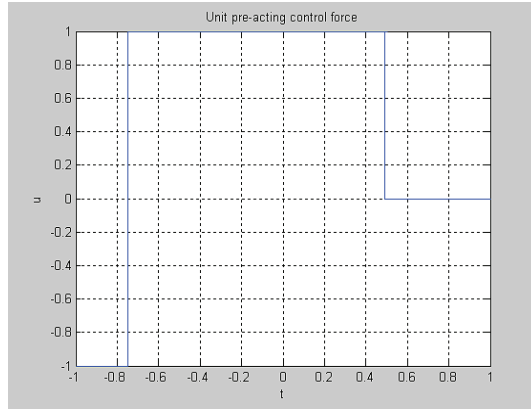


Figure 4 Time History of the Optimal Pre-Acting Control Force

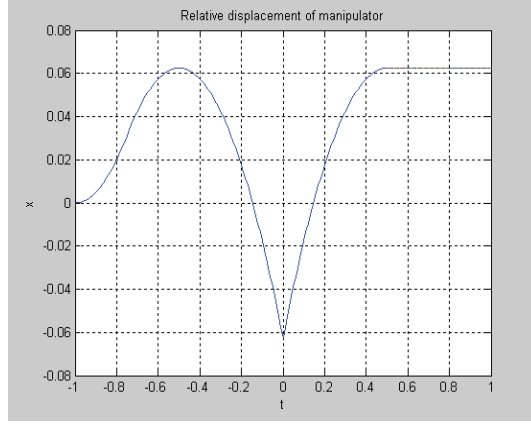


Figure 5 Time History of the Relative Distance of Optimal Pre-Acting Control Force

Figure 5 shows the time history of the relative distance of optimal pre-acting control force.

4. CONCLUSION

In this paper, the dynamics of wire-suspended object was found for estimating the amount of shock and pre-acting control scheme was applied for minimizing the shock from the swinging object, such as H-beams. This topic is very important when using a robot in construction fields, since there are many processes that handle very heavy objects suspended through crane cable. In these cases, the robot should be able to absorb tremendous amount of shock from the swinging object to avoid its damage. The strategy presented in this paper will be valuable components when implementing robotic construction, especially in the assembly of steel beams and columns in high-rise building construction.

5. ACKNOWLEDGMENTS

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SEMI-ACTIVE DIRECT CONTROL OF CIVIL STRUCTURE SEISMIC RESPONSES USING MAGNETO-RHEOLOGICAL DAMPERS

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ABSTRACT

As building structures frequently collapse and cause losses of lives and properties, due to excessive vibrations induced during earthquake periods, it is crucial to reduce the structural vibrations. This paper develops a Lyapunov-based controller for Magnetorheological (MR) dampers embedded in building structures to mitigate quake-induced vibrations. In this work, MR dampers are used as semi-active devices, taking the advantages of the fail-safe operation and low power requirement. To enhance the system performance, a Lyapunov-based controller is proposed here for direct control of the supply currents of the MR dampers placed in a multi-storey building. The effectiveness of the proposed technique is verified in simulation by using a ten-storey building model subject to quake-like excitations.

KEYWORDS

Structural Control, MR Dampers, Semi-Active Control, Lyapunov-Based Control, Seismic Response

1. INTRODUCTION

There has been a large amount of research effort devoted to the development in building and civil infra-structure control. The ultimate objective is the suppression of earthquake induced vibrations or dynamic loading as of wind or heavy traffic [1]. In the review conducted therein, control methodologies applied in buildings are broadly classified into the active [2] and semi-active [3] categories. The former techniques require a certain amount of energy to drive the actuators to accomplish the control objective. On the other hand, semi-active control requires a relatively small amount of driving power and the actuators can also be operated in passive mode. The philosophy adopted in these approaches is to effectively absorb the vibration energy by modifying the control device characteristics. The control devices include fluid viscous, electrorheological (ER) and magnetorheological (MR) dampers. In [4], a comparison was conducted on the efficiency and performance of approaches using semi-active against active tuned mass dampers for building control.

The ER and MR dampers are popular devices in semi-active building control. In essence, they are equivalent in construction to conventional hydraulic dampers except that the characteristics of the fluids can be altered upon the application of currents induced magnetic fields. Although these devices are analogies to each other, the MR damper [5] requires lower voltage which is very attractive for safety and practical reasons. Owing to this advantage, the MR damper is being increasingly employed in vehicle suspension applications [6] where high voltage supplies are not available. In the building control paradigm, the MR damper has also been applied in the passive mode [7] and brace configuration [8].

A recent survey of MR damper controller designs for building control has been published including designs based on Lyapunov stability, decentralised bang-bang, maximum energy dissipation,

modulated homogeneous and clipped-optimal control [9] [10].

In the later approach, the value of the desired force is derived by a linear-quadratic-Gaussian (LQG) controller and a secondary current-control loop is used to derive the appropriate current supplied to the MR damper. All these controllers are affected via the damping force instead of directly controlling the current supplied to the MR damper.

In this work, a Lyapunov-based control strategy will be proposed with the objective to minimise an internal energy function by forcing its time rate of change to be as negative as possible, see, e.g. [11] for structural control with ER materials. For building control with MR dampers, unlike [12], where the MR dampers were characterised by a well-known dynamic friction model, here a current-input model describing explicitly the damper force-velocity relationship [13] is used for direct control of the magnetization currents of the dampers, embedded in a general ten-storey building model. To counteract the force-offset problem for a single damper, a differential configuration is also proposed.

The remainder of the paper is organised as follows. In Section 2, the building structure together with the damper configuration is described. The current-inputs state-space model of the system and the design of the proposed Lyapunov-based controller are presented in Section 3. Simulation results are given in Section 4 to verify the effectiveness of the proposed approach. Finally, a conclusion is drawn in Section 5.

2. SYSTEM DESCRIPTION

2.1 Equation of Motion

Consider a building model subject to vibration under the influence of the ground excitation $\ddot{x}_g$ during an earthquake. Let vibrational displacements of the storeys, x_p, $p = 1,...n$, and n is the number of storeys, be assigned the positive polarity from left-to-right. Each storey has respectively mass m_p, viscous damping coefficient c_p and the stiffness coefficient k_p. These variables are lumped into corresponding matrices $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$. The motion of the building structure can be described by

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{\Gamma}f + \mathbf{M}\mathbf{\Lambda}\ddot{x}_g, \quad (1)$$

where $\ddot{\mathbf{x}}$ is the storey acceleration, $\dot{\mathbf{x}}$ is the velocity and f is the overall force generated by the dampers. Matrix $\mathbf{\Gamma} = \begin{bmatrix} -1 & 0 & ... & 0 \end{bmatrix}^T$ is the gain matrix determining the control effect on the building, and $\mathbf{\Lambda} = \begin{bmatrix} 1 & ... & 1 \end{bmatrix}^T$ is a distribution matrix showing the effect of earthquake acceleration. The equation can be further rewritten in the state-space form by defining a system state $\mathbf{y} = \begin{bmatrix} \mathbf{x}^T & \dot{\mathbf{x}}^T \end{bmatrix}^T$ and is given as

$$\dot{\mathbf{y}} = \mathbf{A}_0\mathbf{y} + \mathbf{B}_0 f + \mathbf{E}_0, \quad (2)$$

$$\mathbf{E}_0 = \begin{bmatrix} \mathbf{0} \\ \mathbf{\Lambda} \end{bmatrix}\ddot{x}_g,\ \mathbf{B}_0 = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{\Gamma} \end{bmatrix},$$

$$\mathbf{A}_0 = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix},$$

Where $\mathbf{A}_0$ is the system matrix, $\mathbf{B}_0$ is the gain matrix and $\mathbf{E}_0$ is the disturbances.

2.2 MR Damper Model

The MR damper is fabricated similarly to a conventional hydraulic damper, i.e., with a moving piston and hydraulic fluid contained in a cylinder. A drawback of damper is non-linear and hysteretic response between the force-displacement and force-velocity relationships. Various models have been proposed to represent the hysteretic behaviour of the MR damper [14][15]. To simplify the design for direct control of the current supplied to the dampers, a static hysteresis model [13] is used in this paper. Accordingly, the damper force generated by damper j is given by

$$\begin{aligned} f_i &= c_{dj}\dot{x}_{dj} + k_{dj}x_{dj} + \alpha_{dj}z_{dj} + g_j \\ z_{dj} &= \tanh\left(\beta_j\dot{x}_{dj} + \delta_j sign\left(x_{dj}\right)\right) \end{aligned}, \quad (3)$$

where the values of damper parameters $c_{dj}, k_{dj}, \alpha_{dj}, g_j, \beta_j$, depend explicitly on the supplied damper current. The relationships between these parameters and the supplied current can be approximated by first- or second-order polynomials.

It is also noticed that due to the need of sufficient travelling strokes to accommodate the frame movement, the dampers have to be connected to the frame in their compressed state. Hence, offset damper forces are produced and may further complicate the controller design. In the sequel, a differential configuration is used to counteract the offset forces as shown in Fig 1.

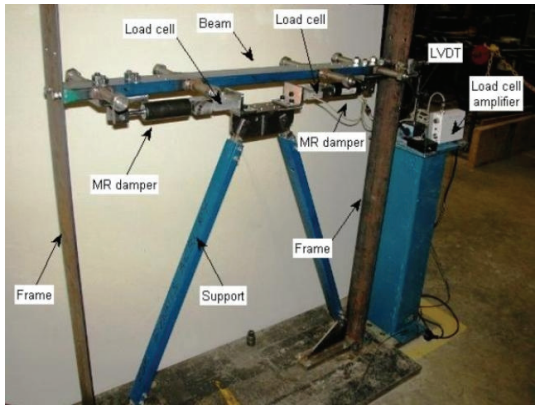


Figure 1 Differential Configuration Implementation of MR Dampers

3. CONTROLLER DESIGN

3.1 State-space Model with Current Input

In the direct control approach proposed in this work, it is assumed that the differential damper configuration is installed on the first storey. The corresponding motion equation, e.g., for the first storey, can be rewritten as below to incorporate the damper current by noting:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -\begin{pmatrix} \bar{c}_{d1}\dot{x}_1 + \bar{k}_{d1}x_1 + \\ \left(\bar{c}_{d2}\dot{x}_1 + \bar{k}_{d2}x_1\right)i + \bar{\alpha}z_d \end{pmatrix} + m_1\ddot{x}_g, \quad (4)$$

where m_1, c_1 and k_1 represent respectively the mass, damping and stiffness of the first storey. By defining the system state $\mathbf{y} = \begin{bmatrix} \mathbf{x}^T & \dot{\mathbf{x}}^T \end{bmatrix}^T$, control current input i and using (4), the state-space equation for the building structure with identical MR dampers installed on the first storey can be written as

$$\dot{\mathbf{y}} = \mathbf{A}\mathbf{y} + \mathbf{B}i + \mathbf{E}, \quad (5)$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\overline{\mathbf{K}} & -\mathbf{M}^{-1}\overline{\mathbf{C}} \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} \mathbf{0}_n \\ -m^{-1}\left(\bar{c}_{d2}\dot{x}_1 + \bar{k}_{d2}x_1\right) \\ \mathbf{0}_{2n} \end{bmatrix}, \ \mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2,$$

$$\mathbf{E}_1 = \begin{bmatrix} \mathbf{0}_n \\ -m_1^{-1}\bar{\alpha}z_d \\ \mathbf{0}_{2n} \end{bmatrix}, \mathbf{E}_2 = \begin{bmatrix} \mathbf{0} \\ \mathbf{\Lambda} \end{bmatrix}\ddot{x}_g,$$

with all elements of $\overline{\mathbf{K}}$ and $\overline{\mathbf{C}}$ remaining the same as of $\mathbf{K}$ and $\mathbf{C}$ in (1), except $\overline{K}_{11} = K_{11} + \bar{k}_{d1}$, and $\overline{C}_{11} = C_{11} + \bar{c}_{d1}$, respectively.

3.2 Lyapunov-based Control Design

Consider the Lyapunov function candidate

$$V = \mathbf{y}^T\mathbf{P}\mathbf{y}, \quad (6)$$

where $V = 0$, if and only if $\mathbf{y} = 0$, $V > 0$, $\forall \mathbf{y} \neq 0$, and $\mathbf{P}$ is a positive definite symmetric matrix to be determined. Now taking the time derivative of V gives

$$\begin{aligned} \dot{V} &= \dot{\mathbf{x}}^T\mathbf{P}\mathbf{x} + \mathbf{x}^T\mathbf{P}\dot{\mathbf{x}} \\ &= \mathbf{x}^T\left(\mathbf{A}^T\mathbf{P} + \mathbf{P}\mathbf{A}\right)\mathbf{x} + 2\mathbf{x}^T\mathbf{P}\left(\mathbf{B}i + \mathbf{E}\right) \\ &= -\mathbf{x}^T\mathbf{Q}\mathbf{x} + 2\mathbf{x}^T\mathbf{P}\left(\mathbf{B}i + \mathbf{E}\right), \end{aligned} \quad (7)$$

where $\mathbf{A}^T\mathbf{P} + \mathbf{P}\mathbf{A} = -\mathbf{Q}$ for $\mathbf{Q} = \mathbf{Q}^T$, $\mathbf{Q} > 0$, is the Lyapunov equation where matrix $\mathbf{P}$ is the solution with a given matrix $\mathbf{Q}$. Furthermore, the choice of matrix $\mathbf{Q}$ can be determined by assigning the rate of decrease of the Lyapunov function V. In addition, using the inequality $\mathbf{y}^T\mathbf{Q}\mathbf{y} \geq \lambda_{\min}\|\mathbf{y}\|^2$, where $\lambda_{\min}$ is the minimum eigenvalue of $\mathbf{Q}$, one has

$$\dot{V} < -\lambda_{\min}\|\mathbf{y}\|^2 + 2\mathbf{y}^T\mathbf{P}\left(\mathbf{B}i + \mathbf{E}\right) \quad (8)$$

By choosing $\mathbf{Q}$ as an identity matrix, i.e., $\mathbf{Q} = \mathbf{I}$, then $\lambda_{\min} = 1$ and the Lyapunov derivative can be expressed as

$$\dot{V} < -\|\mathbf{y}\|^2 + 2\mathbf{y}^T\mathbf{P}\left(\mathbf{B}i + \mathbf{E}\right) \quad (9)$$

In order to obtain a stable system, it is suggested by the Lyapunov stability theory that the derivative should be negative [16], i.e., $\dot{V} < 0$. To satisfy the

requirement of a stable system, an analytical form of the supplied current i can be chosen or it can be cast as an optimization problem of searching for a suitable current value $i \in [0, \quad i_{\max}]$ to minimize the Lyapunov function derivative (7).

$$\begin{aligned} &\text{minimize}: \dot{V}(\mathbf{y}, i) \\ &\text{s.t.}: \dot{V} < 0; 0 \le i \le i_{\max} \end{aligned} \tag{10}$$

For this, to minimise the Lyapunov function derivative, an exhaustive search is conducted on all feasible control current values $i_q \in [0, \quad i_{\max}]$ with some user-specified current precision, where $q = 1,...N$ and N is the number of feasible currents

$$i = \begin{cases} 0, & \text{for } \dot{V}(i_q) > 0 \\ i_q, & \text{for } \dot{V}(i_q) \le 0, q = \arg\min_q \{\dot{V}(i_q)\} \end{cases} \tag{11}$$

4. RESULTS

4.1 System Setup

In the following, for the sake of simulations, a ten-storey building model is used and embedded with one pair of identical MR dampers placed on the first storey, with the parameters of the dampers given in [13]. Therefore, building model parameters are given as

$$\begin{aligned} m_i &= 98.3kg, i = 1...10 \\ c_1 &= 75\,(Ns/m) \\ c_{2...10} &= 50\,(Ns/m) \\ k_1 &= 5.16\times10^5\ (N/m) \\ k_{2...10} &= 6.84\times10^5\ (N/m), \end{aligned} \tag{12}$$

4.2 Controlled Responses

Simulations are conducted on the MATLAB platform using the forth-order Runge-Kutta routine to solve the system differential equation (5) for benchmark records of El-Centro earthquake scaled by 0.5. Fig. 3 shows time responses of the derived current, damping force, Lyapunov function derivative. First storey displacement, velocity and acceleration are also illustrated.

The scaled earthquake record, shown in Fig. 3(a), exhibits a peak approximately at $1.7m / s^2$ and endures $30s$. The applied damper current is illustrated in Fig. 3(b) which is always positive and smaller than $i_{\max} = 2A$ as required. Fig. 3(c) depicts the force generated from dampers and presents a resemble of the earthquake. The Lyapunov function derivative is shown in Fig. 3(d) indicating the system stability in most of the earthquake period except where the magnitude is too large. However, the derivative returns to negative and the building structure under control becomes stable. The first storey displacement, velocity and acceleration are shown in Fig. 3(e). The responses (solid lines) display reductions in displacement, velocity and acceleration as compared to the no control responses (dotted lines). As can be seen from Fig. 3(e) that by using the proposed Lyapunov-based control, the reduction in quake-induced displacement is remarkable compared to that from no control.

4.3 Evaluation Criteria

The effectiveness on reductions in earthquake induced vibrations on the building structure is further evaluated by a set of performance indices comparing the control response against the results obtained from an un-controlled case. The criteria, adopted from [10], encompass ratios of storey displacements and accelerations. They are formulated as follows:

1. *Absolute storey displacement ratio*

$$J_1 = \frac{\max\{|x_{k,c}(t)|\}}{\max\{|x_{k,u}(t)|\}} \tag{13}$$

where the subscript $k = 1...10$ stands for the storey index and subscripts c, u denote controlled and un-controlled displacement.

2. *Absolute storey acceleration ratio*

$$J_2 = \frac{\max\{|\ddot{x}_{k,c}(t)|\}}{\max\{|\ddot{x}_{k,u}(t)|\}} \tag{14}$$

where the notation $\ddot{x}$ presents the storey acceleration.

3. *Inter-storey drift ratio*

$$J_3 = \frac{\max\{|\bar{x}_{k,c}(t)|\}}{\max\{|\bar{x}_{k,u}(t)|\}} \tag{15}$$

where the inter-storey displacement is given by $\bar{x}_1 = x_1,\ \bar{x}_{k>1} = x_k - x_{k-1}$.

4. *Root-mean-squared storey displacement ratio*

$$J_4 = \frac{\tilde{x}_{k,c}(t)}{\tilde{x}_{k,u}(t)} \tag{16}$$

where the root-mean-square (RMS) values are calculated from $\tilde{x} = \sqrt{T^{-1}\sum\{\delta_t x_k^2(t)\}}$, δ_t is the sampling time and T is the total excitation duration.

5. *RMS storey acceleration ratio*

$$J_5 = \frac{\tilde{\ddot{x}}_{k,c}(t)}{\tilde{\ddot{x}}_{k,u}(t)} \tag{17}$$

where the RMS values are calculated as above.

Table 1 Response ratios: (a) Current $i = 0$; (b) Current Generated from Lyapunov-Based Controller

Floors / Criteria	J_1	J_2	J_3	J_4	J_5
1st	0.75	0.55	0.75	0.53	0.38
2nd	0.76	0.58	0.78	0.54	0.40
3rd	0.77	0.63	0.79	0.55	0.43
4th	0.78	0.67	0.81	0.55	0.47
5th	0.79	0.69	0.76	0.56	0.51
6th	0.82	0.72	0.72	0.56	0.55
7th	0.81	0.76	0.68	0.56	0.56
8th	0.75	0.55	0.75	0.53	0.38
9th	0.76	0.58	0.78	0.54	0.40
10th	0.77	0.63	0.79	0.55	0.43

(a)

Floors / Criteria	J_1	J_2	J_3	J_4	J_5
1st	0.47	0.49	0.47	0.28	0.33
2nd	0.53	0.44	0.68	0.35	0.32
3rd	0.58	0.52	0.71	0.38	0.34
4th	0.62	0.53	0.71	0.41	0.38
5th	0.64	0.60	0.60	0.42	0.42
6th	0.65	0.61	0.58	0.43	0.45
7th	0.64	0.67	0.52	0.43	0.46
8th	0.62	0.64	0.49	0.44	0.45
9th	0.61	0.52	0.57	0.44	0.44
10th	0.61	0.57	0.68	0.44	0.44

(b)

Comparisons of evaluation criteria between the passive mode $(i = 0)$ and semi-active mode (the proposed Lyapunov-based controller) are provided in the Table above, as can be seen from the table, all the corresponding ratios with Lyapunov-based controller are much smaller than that with no control $(i = 0)$

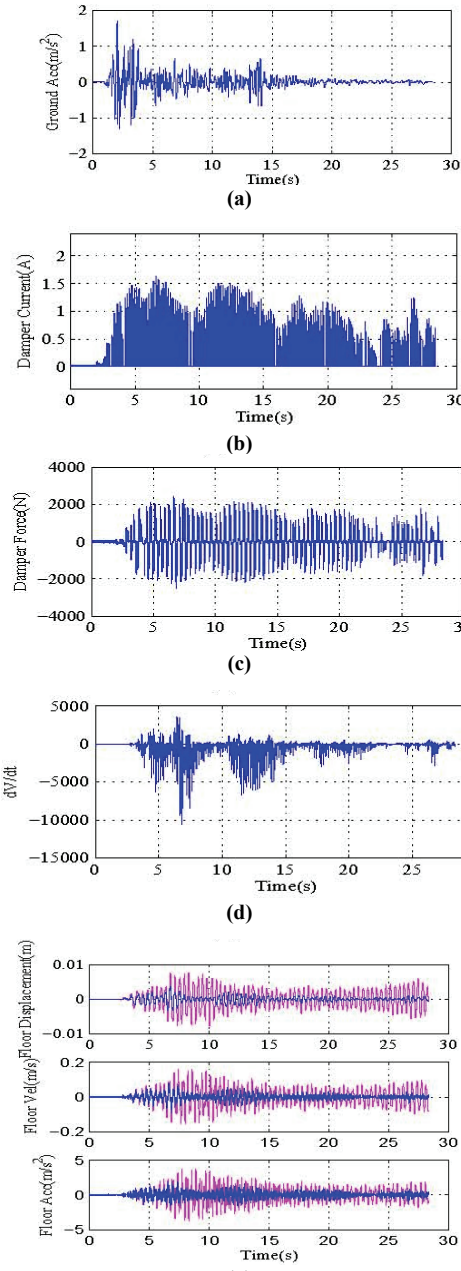


Figure 3 El-Centro Responses: (a) Earthquake Record, (b) Current, (c) Damper Force, (d) Lyapunov Function Derivative, (e) 1st Storey Displacements, Velocity and Accelerations

5. CONCLUSION

This paper has presented an effective semi-active control approach for building structures embedded with MR dampers for mitigation of the vibrations induced from seismic excitations. Furthermore, a Lypunov-based controller is designed such that the supplied currents to the dampers can be directly controlled for improved performance, making use of a static hysteretic model for MR dampers. Promising results obtained indicate the prospective use of MR dampers as semi-active devices in smart structures in quake-prone regions.

6. ACKNOWLEDGMENT

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SIMULATION OF THE RESISTANCE FORCES OF BULK MEDIA TO BUCKET IN A LOADING PROCESS

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ABSTRACT

In this work the process of penetration of a bucket into bulk media (for loading or excavation) is simulated based on the forces that are involved in the process. The main objective is to simulate the resistance force of medium to cutting by a tool (bucket/blade) during a loading or excavation process. The work stems from an initial purpose to evaluate the effectiveness and performance of a strategy for automation of loading of bulk media (autoloading) by an excavator. In addition to serving for that purpose, the results of this work can be used in the development of training simulators for construction and excavation machines that include animation of the motion of a bucket, but lack the behaviour of the material during the process.

The encountered resistance by a tool (bucket) dictates its motion. The medium resistance can change significantly even within a small area and it depends on the tool orientation. If not controlled, the cutting tool follows the path with the least resistance. For this simulation a planar motion is considered for the sake of simplification of the complicated process. As can be depicted by a number of examples, the paper shows that the simulation is valid and can be successfully used.

KEYWORDS

Simulation, Resistance Force, Bulk Media

1. INTRODUCTION

The problem of automation of loading by a cyclic excavator, such as a front-end-loader, has been the subject of research for more than a decade. Yet, no commercial product has been introduced to the market so far, nor a breakthrough has been reported on the subject. One reason for this is the complexity nature of the process and the fact that the essential research is time consuming and costly.

As a necessary part of research in this matter one has to examine the effectiveness of any control strategy as well as comparing various proposed control techniques. As a tool to facilitate such an evaluation and comparison, simulation software can speed up the process and determine the functionality of a control strategy at the primary step.

This work is related to what becomes necessary for simulation of the loading/excavating by a machine to be automated. It simulates the interaction between a medium and a cutting tool or blade that must overcome the resistance from the medium during loading (cutting, penetrating and scooping).

Simulation of properties of materials has become a popular way for research on many different studies to be performed. Nevertheless, the scope of application is so vast and the results for one application can be far from what is required in another. These are mostly offered in the form of commercial simulation packages for a particular application. For instance, modeling and simulation solutions for studying chemicals and materials can

be at the level of molecular bonding and crystal structure, the process of crystallization, and structure-activity relationships, although all these are indeed material simulation. Or the work can focus on the formulation of deformation and fluid flow. Also, it could be concentrated on metals, a temperature treatment on metals, or the emphasis could be on certain class of material, such as bio-materials. There are plenty of references associated with simulation and materials, two keywords of this paper, but there is no point referring to any publication that is not directly related to this work. As for the objective of this paper not much previous work can be addressed.

2. APPLICATION OF THIS WORK

The results of this work can be used for applications that call for simulation of a tool or bucket interfacing with bulk media. As mentioned before, the main purpose has been using this as a tool for examination/ verification of the effect of a control policy for loading particulate media. Another very important application is in the simulators that are employed for training of operators for large excavating mashines. These days, similar to a flight simulator for training of pilots, for many such machines, like a backhoe or grader, it is much more cost effective to train an operator on a simulator, first, before he gets on to the real machine. The results of this work can be integrated with such software. In this way, when the operator trainee runs the cutting tool (blade, bucket, etc.) through the soil or fragmented rock, the software makes a distinction between moving through a medium and moving through the air.

Furthermore, based on this work, the training simulator can be enhanced through feedback of the forces exerted to the loading element to the levers, pedals and the like. In this way the trainee feels the effect of his actions in a more realistic manner.

3. LOADING RESISTANCE FORCE

When a tool is in contact with a medium the cutting edge of the tool has to interface with the medium (Hereafter the world tool will be used for the cutting element in an excavator, whether a blade, a bucket or other, depending on the machine). So, the cutting edge encounters a force that must be overcome in order for the tool to penetrate into or cut through the medium. This force must be provided by the driving elements/actuators on the excavating machine. This, however, is not the only force that must be overcome and must be provided by the actuators. Depending on the machine and the cutting tool form and size a number of resisting force components exist which have a resultant at the actuator level. The actuator, thus, must provided an active force superior to the total resistive force. For a bucket in a front-loader or a loader type excavator these force components are shown in figure 1 and are as follows [1]:

r_1: The weight of the material in the bucket

r_2: the force of the bucket body pushing (and compressing) the material

r_3: Friction forces of the material moving into the bucket

r_4: Cutting force

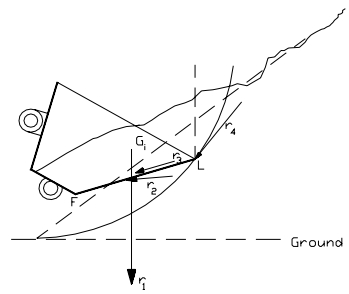


Figure 1 Forces From Media of a Bucket

In addition to these, the active forces of the excavating machine must move the bucket, its contents and the material above the bucket that moves with the bucket. Analysis, formulation, and experimental measurement of excavation force components has been vastly studied by Zelenin et al [2] in earlier decades and more recently a number of researchers have worked on the subject (see for instance [3][4])

When the active force from the actuator and the resistive force from the medium come to an interaction then the behaviour of the machine and the medium has to follow the physical laws. In this respect, the machine has stiffness and damping that can lead to its deformation. So has the medium that undergoes a physical change. Figure 2 shows the model for the tool-medium interaction. For the medium, nevertheless, the stiffness is

relatively very low and damping is relatively very high.

The model shown in figure 2 is for a simple system comprising a single actuator. In practice, usually there are more than one actuators and the necessary treatment must include the whole system. As a result, the simulation becomes more involved, as well as more meaningful. As for example, when the bucket of a back-hoe or a loader moves the motion is not necessarily a straight line and the direction of all the force components vary at each instant. For this reason, the simulation code is machine dependent. That is, the simulation code (this software) should be integrated with the code for moving the various actuators in a machine.

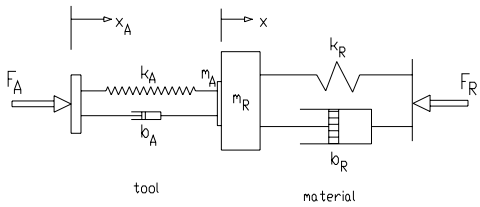


Figure 2 Tool-Medium Interaction Model

In this simulation a small front loader is used as the device the bucket of which interacts with the soil. The conceptual design of this machine is shown in figure 3, depicting the extreme lower and upper reach positions of the bucket and the dimensions. For simplicity the loading motion of the bucket is assumed to take place in a plane. In fact, such a machine has three degrees of freedom which lead to a planar motion of the bucket. The schematic of a model of this machine is illustrated in figure 4. Figure 4 is a model of the loading gear in a front-end loader excavator consisting of a prismatic joint representing the advance motion of the vehicle and two linear actuators leading to rotating motion of the bucket. Thus, the loader is represented by a robotic arm having one prismatic and two revolute joints. All the definitions for various dimensions are shown also in figure 3. The associated modeling definitions, kinematics and force relationships for this class of excavator are given in [1].

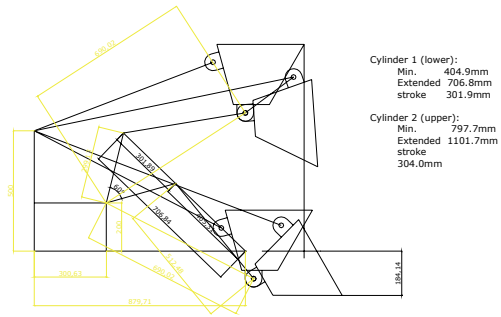


Figure 3- Schematic of a Model Loader

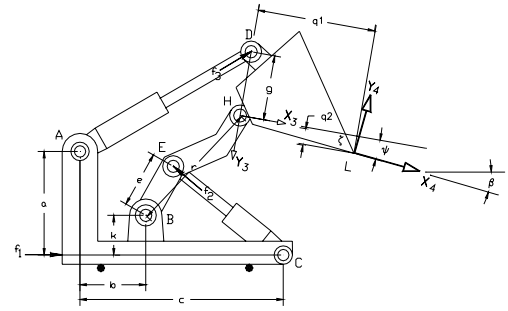


Figure 4 Robotic Model of a Loader

4. SIMULATION ANALYSIS

In the simulation we are introducing a force (either fixed or variable) to each actuator and also we define the medium properties in the form of a force vector, then the movement of the bucket under the effect of this force is considered and recorded.

Out of the five force components that were mentioned in the previous section and are shown in figure 1, the component r4 (representing the resistance to the cutting blade) is the dominant force. Since the simulation at the current stage (the objective of this paper) is for the medium resistance, considering this force component, only, is acceptable. Otherwise, the effects of the weight of the loaded material and the friction forces must also be included. The effect of the weight change can be included in the mass parameter that is used as a rigid body on which the resultant of actuators forces acts.

In the simulation, we assume that the loading is to take place from a heap of soil. Thus, the force r_4 depends on the location of the point of action inside the heap and, more importantly, if the bucket is driven out of the heap then the motion takes place in the air, for which there is no resistance. The nominal values of the soil at a number of specified mesh points are defined as 3-element vectors: two force components and a torque component. The given data are in the form of a matrix of force vectors for a limited number of points. The software generates more points, as desired, by linear interpolation from the surrounding mesh points. Since two-dimensional motion is considered, all the force components along the width of the bucket are taken as to be the same. As a result of the above, the input data does not have a large size, taking away the burden for the necessity of defining a large data base for the soil force

At each node three values for a horizontal force, a vertical force and a torque are defined. These are for the resistance to the motion of a bucket with zero orientation (β = 0; see figure 4). In the process as the bucket moves and its orientation of changes, the corresponding force/torque elements on the cutting edge are calculated and adjusted.

The excavation force encountered by an excavating element can significantly vary from point to point inside a medium. For this reason, at any point a random value is added to the nominal force values. In the simulation this randomly generated value was always positive, but its range of variation was quite large. Since the simulation is for the medium resistance, we are not concerned about the flexibility and damping of the structure of the bucket and its driving linkages. In this way, we can assume that the active force of each joint is readily available when transformed at the tool cutting edge. As for the flexibility and the damping in the medium, the material is less likely to perform like a spring and push back the bucket. In fact, when the active force is more than the resistive force, then a motion results, but when the active force is inferior to the resistive force, there is no backward motion; there will be no motion, instead. In this sense, it is reasonable to assume that the medium stiffness is very small (material deforms) such that it can be ignored in comparison with damping constant. A nominal value for the damping can be selected such that the motion is sufficiently damped.

5. EXAMPLES

The model loader used can raise its bucket by 0.874m from ground. An advance motion of 1.500 m seems to be reasonable for loading. Also, there is 60° orientation change from a horizontal (ready for loading, β = 0) configuration to filled configuration (β = 60). The bucket motion is dictated by the lengths of the actuators at each instant. For the two cylindrical actuators if at any time the minimum or maximum length is reached no more retraction or extension can take place.

In the examples that follow the bucket of the model loader is run into the medium without any control. The outcome is, thus, a motion governed by the difference between the active forces provided by the actuators and the resistive forces at the bucket cutting edge transformed to coordinates at the actuator level.

Simulation is carried out at two levels by any number of desired steps. The reason for having two levels is to allow for changing the active forces, effective mass values and so on. The number of steps represent the duration of operation. This duration is the same in all the examples. In the following illustrations the graphs representing the results of the simulation reflect the motion of the bucket in the horizontal and vertical directions, measured in metre.

5.1 Example 1

In this example the actuator forces, vehicle push, first cylinder push and second cylinder pull, respectively, are 2000, 1500 and 1500 from the beginning and stay constant for the whole time of simulation. Metric units are used. The effective mass values are increased by 10% for five times, evenly spaced during the period.

In this example the initial values of the actuator forces have not been sufficiently large to give rise to a noticeable motion of the bucket. The bucket has hardly changed orientation or moved in the vertical direction.

Figure 5 shows the position (x and y-coordinates) of the cutting edge of the bucket and its orientation at the starting point. The numbers represent the

displacement in meters, in the horizontal and vertical directions. All the examples have the same starting configuration. As is depicted by negative values shown in figure 5, the bucket has stayed below the vehicle platform, near the ground. In other words, the active forces have not been sufficient to move the bucket through the medium (for loading).

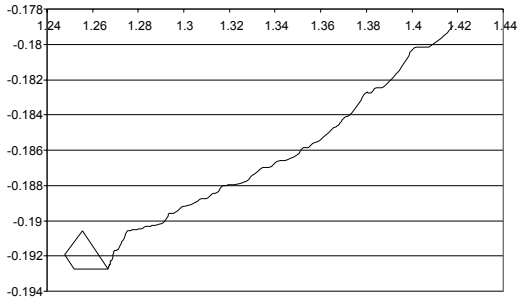


Figure 5 Bucket Motion for Example 1

5.2 Example 2

For this example all the data are the same as before except for the active forces provided to the actuators that are increased five times by 20% in each step. The bucket movement and its orientation at a few points are shown in figure 6. In this case the bucket has maneuvered a complete loading cycle by the time it is in the forth position shown.

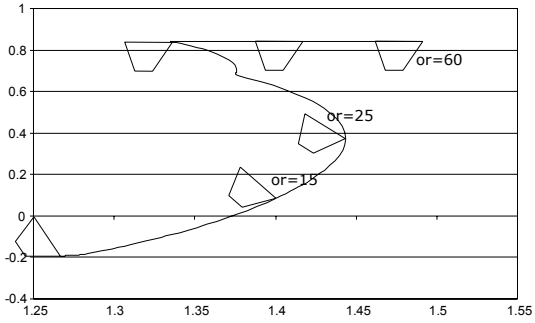


Figure 6 Bucket motion for Example 2

In this position, the linear actuators have reached their limits and, thus, the orientation has not changed afterwards, but the bucket has been pushed further forward. At the level of this paper, we are not concerned about if the motion is correct or if the bucket is filled. Obviously, the forces are not determined beforehand and the process is not controlled. What we are interested in is that if the simulation of the behaviour of the material is reasonable. From the figure we may realize that during the first portion of the motion the forward push of the bucket has not been sufficient or, saying it differently, the forces of the actuators 2 and 3 have been more than necessary.

5.3 Example 3

In this example it is assumed that the same force scenario as in example 2 is used, with the exception that the material is heavier. The variable representing the material mass are five (5) times larger than those in example 2. Everything else (except the random values that determine the final resistive force) is the same as in example 2. The results are shown in figure 7. The bucket has stopped at the final point shown, meaning that for the period (simulation duration) the bucket could be moved only halfway. The motion has to be continued for completion.

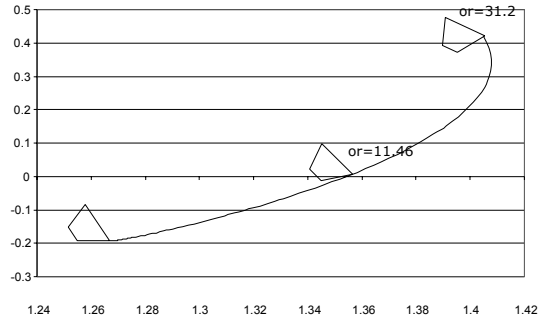


Figure 7 - Bucket Motion for Example 3

5.4 Example 4

Two changes have been introduced here compared to the previous example. The stepwise increases in the actuators and mass have been modified from 20% and 10%, respectively, to 33% and 20%. The outcome is depicted in figure 8.

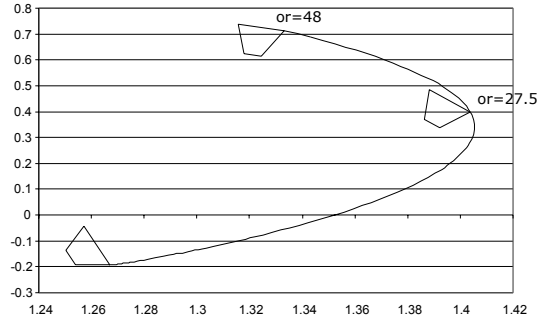


Figure 8 - Bucket Motion for Example 4

5.5 Example 5

The material density related values (mass representations as well as damping coefficients) have been further increased from its values in example 4; they have been doubled, for a heavier substance. The results are depicted in figure 9, which show a reasonable change (note that the motions for all the three degrees of freedom are smaller).

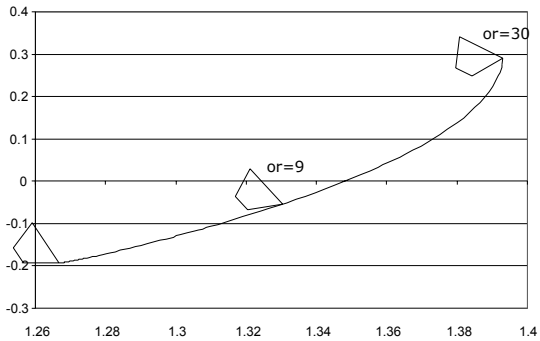


Figure 9 Bucket Motion for Example 5

5.6 Example 6

For the final example, we have kept all the characteristic data of example 5, except that the initial forces have all been increased by 200 units. As a result, the bucket has been moved further, particularly, the actions of the linear actuators are more pronounced.

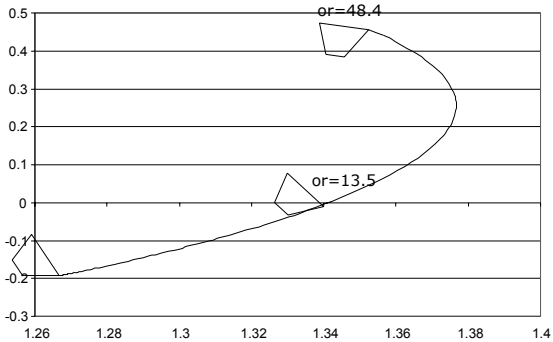


Figure 10 - Bucket Motion for Example 6

6. SUMMARY AND CONCLUSIONS

The process of interaction of a tool with a medium is complicated. The resistive force components involved depend on the tool orientation when a blade or bucket is moved.

These facts are brought into consideration in a software developed for simulation of the behaviour of a medium to cutting in a loading or excavation process. The simulation software is machine dependent. The paper discusses the more important points and the general approach. It shows that the simulation is valid and can be successfully used, as can be depicted by a number of examples. As such, the methodology and the simulation code may be incorporated with the training simulator software for any type of machine interfacing with bulk or particulate material. As well, it can serve for the purpose of evaluating the control strategies for loading automation and so on.

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OPTIMAL PATH PLANNING FOR BACKHOE BASED ON EXCAVATION ENVIRONMENT

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ABSTRACT

The paper focuses on the establishment of optimized bucket path planning using numerical solution method, for a force-reflecting backhoe which is affected by excavation environment including potential obstacles. The developed path planning method can be used for precise bucket control and more importantly for obstacle avoidance which is directly related to safety issues. An optimal path planning model to minimize energy and to move manipulator arms along a specified path subjected to angular constraints was first established. Simultaneously, path modification due to unexpected obstacles was considered. A Newton-Raphson iteration method was used to acquire angular information of boom, stick, and bucket to solve inverse kinematics. The model presented in this paper was intended to be implemented in further study of force and vibration feedback control of tele-operated excavator using haptic devices.

KEYWORDS

Obstacle Avoidance, Joint Constraint, Jacobian Pseudo-Inverse, Path Planning

1. INTRODUCTION

Excavation of large area by human operator not only takes a lot of time, but also can lead to high labor cost. In addition, excavation environment is recognized as one of the most hazardous construction environment. Therefore, automation of excavation is essential to resolve both time and economic inefficiency and potential risks inherited in excavation environment. Many efforts have been made on development of automated and intelligent excavator [1, 2, 3]. One of the requisites for the accomplishment of fully automated excavation environment is establishment of optimal path planning of excavator. Optimum path algorithm must be constructed in a way of energy efficient and also obstacle avoidance ready. To attain both goals, numerical method was used for deriving solutions of inverse kinematic problem.

For a redundant manipulator there are infinite numbers of solution exist. Backhoe can be classified as redundant manipulator for the reason that it has 4 DOFs including swing, boom, stick, and bucket rotational commands, while there are three independent variables to describe the motion of the manipulator. As the method for acquiring solution, Newton-Raphson iteration was used to find minimum norm solutions for commanded end-effector motion. Minimum norm solution is not always the best choice when there is a potential obstacle inside the manipulator workspace or divergences of solution occurs due to near singularity configuration of links. Therefore, it is important to achieve the second goal of obstacle avoidance and the third goal of moving the links within joint angle limits while

satisfying the first goal of moving end-effector to desired position and orientation. Successful task is therefore defined as achieving all of these goals simultaneously with smooth conversion between them. Setting boundary of joint angle limit prevents manipulator from undergoing serious damage of equipments due to robust motion. For discriminating proper joint angle limits within the joint null space, a scheme to obtain directionality of joint angles with respect to end-effector motion was established. Simulations were conducted to verify the joint directionality identification scheme. Assignment of link and joint variables, joint axes was built upon Denavit-Hartenberg notation [4].

2. THEORY

The end-effector position and orientation vector for manipulator can be expressed by *m* by 1 matrix, where *m* equals 6 in general case of redundant manipulator in Cartesian space. Joint-space vector can be represented as *n* by 1 matrix where *n* corresponds to degrees of freedom the manipulator has. An equation which relates Cartesian vectors $x_e(t) \in R^m$ to joint space vectors is $\theta(t) \in R^n$ as the following.

$$x_e(t) = f(\theta(t)) \tag{1}$$

By taking time derivatives of each parameter, linear correspondence between Cartesian space vector and joint space vector can be achieved.

$$\dot{x}_e(t) = J_e \dot{\theta}(t) \tag{2}$$

where J_e is *m* by *n* end-effector Jacobian matrix. The general solution to the equation (2) is given by Rao et al. [5],

$$\dot{\theta}(t) = J_e^{+} \dot{x}_e(t) + (I - J_e^{+} J_e) z \tag{3}$$

where J_e^{+} denotes the Moore-Penrose pseudoinverse given by $J_e^{+} = J_e^{T}(J_e J_e^{T})^{-1}$, J_e matrix is $m < n$ according to (2), which means manipulator is redundant. $(I - J_e^{+} J_e)$ is projection operator which chooses vectors from *z* and send them to null space to satisfy (2). *z* is an arbitrary vector in joint space, which can be altered properly as far as it is located in the space of homogeneous solution. Yoshikawa [6] has implemented obstacle avoidance scheme for selecting vector *z*, which mainly describes the relationship between *z* and specified velocity vector moving to collision-free or safe place. The minimal obstacle distance was obtained earlier by Hanafusa et al. [7], and vector *z* was given by

$$z = [J_o (I - J_e^{+} J_e)]^{+} (\dot{x}_o - J_o^{+} J_e \dot{x}_e) \tag{4}$$

where J_o is obstacle Jacobian which is formulated from specified velocity vector acting to critical point on link. The location of critical points were described in paper by Zhang et al. [8]. Maciejewski et al. [9] put multiple obstacle avoidance scheme upon work by Hanafusa et al. [7]. By substituting (4) into (3),

$$\dot{\theta}(t) = J_e^{+} \dot{x}_e(t) + (I - J_e^{+} J_e)[J_o (I - J_e^{+} J_e)]^{+} (\dot{x}_o - J_o^{+} J_e \dot{x}_e) \tag{5}$$

3. IMPLEMENTATION

While implementing the theory, it was found that the directionality of distal point of specific links or joints can be recognized and selected by substituting J_o with J_k where *k* is the joint number [*k*= 2, 3, ...] in control. Firstly, two

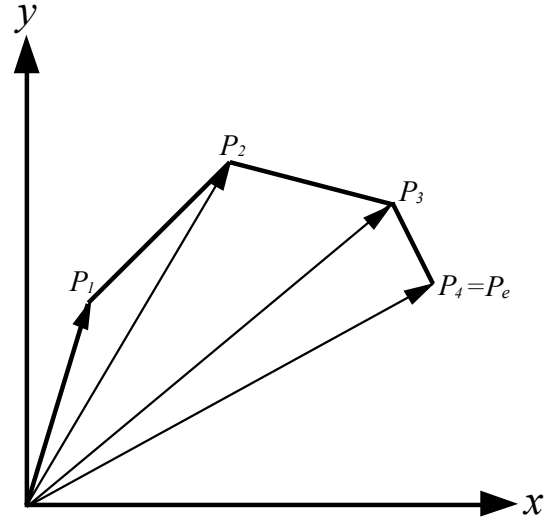


Figure 1 Definition of P_k for 4 Link Manipulator

dimensional redundant manipulator having four links was considered. Components of J_k matrix was given by,

$$J_k = \begin{bmatrix} \frac{\partial P_{k,x}}{\partial \theta_1} & \frac{\partial P_{k,x}}{\partial \theta_2} & \frac{\partial P_{k,x}}{\partial \theta_3} & \frac{\partial P_{k,x}}{\partial \theta_4} \\ \frac{\partial P_{k,y}}{\partial \theta_1} & \frac{\partial P_{k,y}}{\partial \theta_2} & \frac{\partial P_{k,y}}{\partial \theta_3} & \frac{\partial P_{k,y}}{\partial \theta_4} \end{bmatrix} \quad (6)$$

It can be seen from Fig. 1 that $P_k = [P_{k,x}, P_{k,y}]^T$ is vector of joint number *k* from its origin. J_k cannot be directly obtained by differentiating P_k with respect to θ_l; where *l* = 1, 2, 3, 4 for 4 link manipulator. The reason is for the case $k < l$, when deriving partial derivative of P_k with respect to *l*-th variable of θ, every elements in *l*-th column of becomes zero, which makes J_k meaningless. There are two ways to express coordinates of P_k in Cartesian space. That is to either use direct kinematics and represent the position vector with respect to origin or inverse kinematics and represent the position from end-effector.

$$P_k = \begin{cases} P_k, & if \quad k \geq l \\ P_e + P_k^e, & if \quad k < l \end{cases} \quad (7)$$

As shown in Fig. 2, P_e is end effector point and P_k^e is vector from P_e to P_k. Both vectors are pointing at a same spot in terms of Cartesian coordinate but having different orientation. This orientation difference is a key thing for valid formulation of. J_k. That is, when taking partial derivatives of P_k from (7) with respect to θ_l there were no more null elements in the *l*-th column of Jacobian J_k. Instead of Maciejewski's implementation [9] of obstacle avoidance scheme upon Yoshikawa's work [6], end point velocity of links can be substituted into (5) with gain added to each terms.

Jacobian relating $\dot{x}_k(t)$ and $\dot{\theta}(t)$ is given by

$$\dot{x}_k(t) = \lim_{t \to 0}[dP_k / dt] \quad (9)$$

where J_k is represented by (6), and

$$\dot{x}_k(t) = J_k \dot{\theta}(t) \quad (8)$$

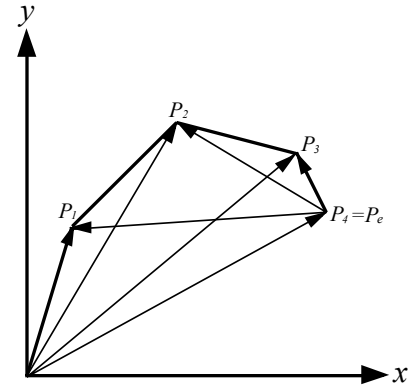


Figure 2 Two Vectors Pointing at a Same Point

Let minimum norm solution satisfying goal for obstacle avoidance, in the second term in (5) as H_o. Then,

$$H_o = (I - J_e^+ J_e)[J_o(I - J_e^+ J_e)]^+ (\dot{x}_o - J_o^+ J_e \dot{x}_e) \quad (10)$$

Likewise, H_k ; the minimum norm solution satisfying goal for each link, is given by

$$H_k = (I - J_e^+ J_e)[J_k(I - J_e^+ J_e)]^+ (\dot{x}_k - J_k^+ J_e \dot{x}_e) \quad (11)$$

Modified general solution yields,

$$\dot{\theta}(t) = s_e J_e^+ \dot{x}_e(t) + s_o H_o + \sum_{k=1}^{n} s_k H_k \quad (12)$$

where, *s* subscript denotes respective gain for each term depending on link configuration, which is going to be dealt with later on. $\dot{x}_k(t)$ should be assigned in an adequate manner so as to satisfy goal of constraining each joints regardless of end effector motion. To achieve the goal, relation between directionality of each joints and end effector motion should be defined first. Fig. 3 shows an example when *k*=1, that is where rotation of link 1 is concerned. New coordinate frame $x_{ke} - y_{ke}$ was defined. x_{ke} is an axis passing through both points P_k and P_e, and y_{ke} axis is an axis perpendicular to x_{ke} axis and passing through point P_e which is current end effector point.

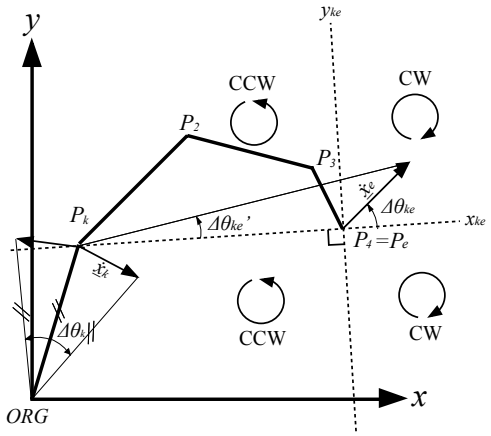


Figure 3 Estimated Rotation of Link 1 w.r.t. ORG Due to End-Effector Movement When *k*=1

If $\Delta\theta_{ke}$, which is an angle made by $\dot{\vec{x}}_e$ and x_{ke} axis, is at 1st or 4th quadrant, link k is rotated clockwise with respect to joint axis k-1 from current position. Otherwise when $\Delta\theta_{ke}$ is at 2nd or 3rd quadrant, link is rotated counter-clockwise as you can see in Fig. 3. For clarity, the following equation was constructed.

$$\dot{x}_k(t) = -D\frac{1}{M}\mathrm{sgn}[P_e^k \square \dot{x}_e]\Delta\theta_{ke}{}' P_k^{k-1} + \dot{x}_{k-1}(t) \quad (13)$$

where D is the directional operator and M is the Joint angle magnification factor, and

$$\Delta\theta_{ke}{}' = a\tan 2\left[\frac{\left\|P_e^k \times [\dot{x}_e + P_e^k]\right\|}{\left\|P_e^k\right\|\left\|\dot{x}_e + P_e^k\right\|}, \frac{P_e^k \square [\dot{x}_e + P_e^k]}{\left\|P_e^k\right\|\left\|\dot{x}_e + P_e^k\right\|}\right] \quad (14)$$

The joint directional operator D takes either +1 or -1 depending on user objectives, as is stated on the following.

$$D = \begin{cases} +1, & \text{if want to add robustness and directionality to the motion of link k} \\ -1, & \text{if want to hold the current position of link k} \end{cases} \quad (15)$$

Equation (13) is based on the assumption that

$$\left\|\dot{x}_e\right\| = \left\|\dot{x}_k\right\|. \quad (16)$$

To satisfy the condition (16), variable M was used. As can be seen in Fig. 4, M was constructed from

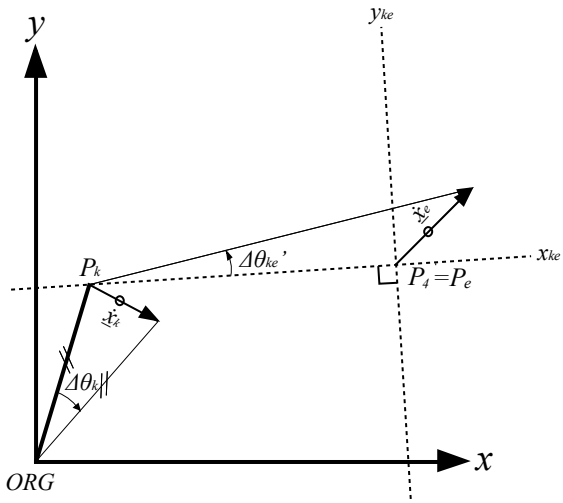


Figure 4 Relation Between Angle Variations, $\Delta\theta_{ke}{}'$ and $\Delta\theta_k$ for the Definition of *M* when *k*=1

simple relationship between angular velocity and linear velocity. For small angle variation of $\Delta\theta_{ke}{}'$.

$$\lim_{\Delta\theta_{ke}\to 0}\left\|\dot{x}_e + P_e^k\right\| = \left\|P_e^k\right\| \quad (17)$$

$$M \cong \frac{\left\|P_e^k\right\|}{\left\|P_k^{k-1}\right\|} \quad (18)$$

4. RESULTS

Before applying joint directionality scheme to backhoe model, simulation for 4-link manipulator was conducted. For clarity, simple point to point command with single point obstacle was considered. One hundred times of iteration was applied to verify stability of the system. Respective gains for each term which is denoted as s subscript was changed properly for respective purpose of tasks. Firstly, by setting every gain terms to zero except for end effector gain, manipulator arm ignored the point obstacle while moving to commanded end effector point.

Results for second case which is to verify the effectiveness of s_o (gain for obstacle avoidance term) for the system can be seen in Fig. 5. As it can be seen, end effector has failed to reach the commanded point. Even by adding more numbers of iteration, end effector could not turn around the half circle of obstacle avoidance point completely.

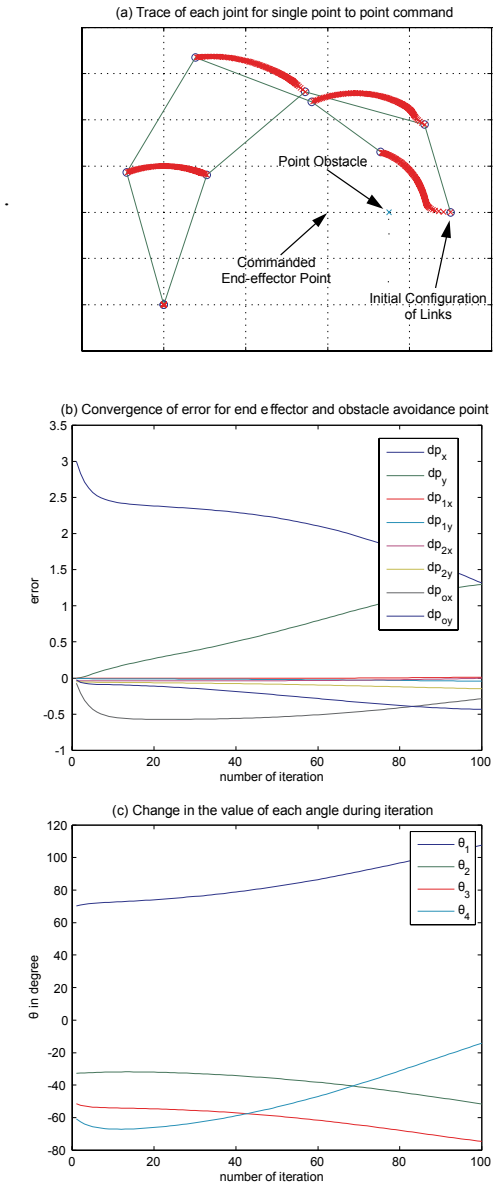


Figure 5 Simulation Results Without Applying Joint Directionality Scheme ($s_1 = s_2 = 0$, $s_o = 0.2$)

Lastly, by setting s_1 and s_2 to 0.01, the model could reach the desired point without passing through obstacle region, and with desired path. Furthermore, the system was stabilized only after about 25 times of iteration. It was noticed in Fig. 6-(c) that small oscillation arises for each angle. The oscillation is due to the recursive characteristic of numerical method which is minimizing errors for every term simultaneously, which does not seem to affect much to the stability of system.

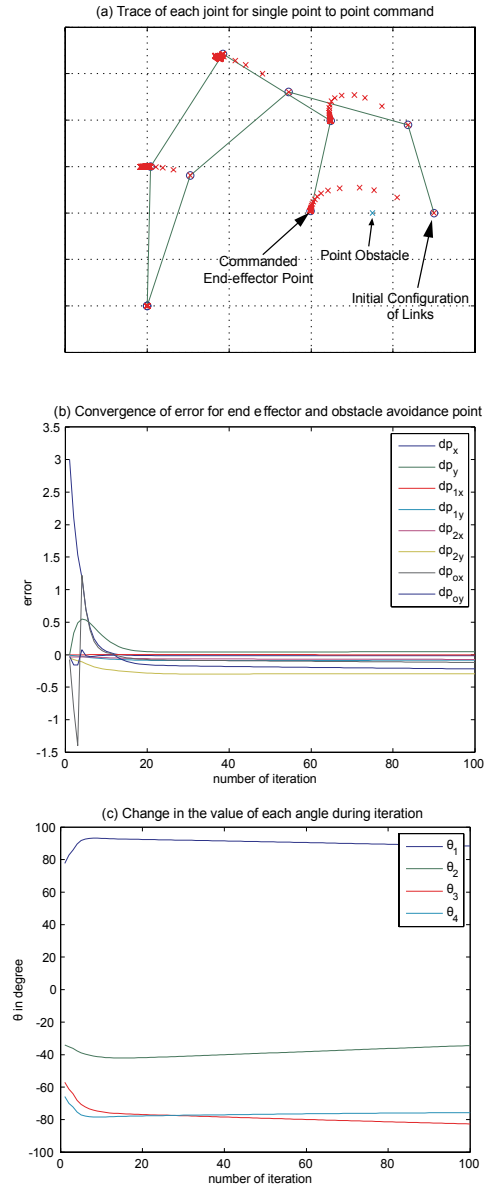


Figure 6 Simulation Results with Applying Joint Directionality Scheme ($s_1 = s_2 = 0.01$, $s_o = 0.2$)

5. CONCLUSION

Overall, as can be seen in the simulation results, joint directionality scheme has proven to be an effective approach for joint constraint and

obstacle avoidance. In spite of the fact, further research is required to apply the scheme to real backhoe model. Real backhoe model can be thought of as a 4-link manipulator consisting of three links moving within a plane created by rotation of one link; swing motion, about *z*-axis. Therefore, there is discrepancy between real backhoe model and the one considered on this paper. Therefore, the discrepancy must be removed in further study. Besides, criterion for assigning adequate gain terms for each link, in equation (12), must be defined.

6. ACKNOWLEDGMENT

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DESIGN OF A HAPTIC DEVICE FOR DISMANTLING PROCESSES USING EXCAVATOR

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ABSTRACT

Since the processes of dismantling are very dangerous, there have been many studies to develop remote operating devices using joystick. In this paper, in order to improve the operability of the dismantling equipment that is usually an excavator, a novel concept of tele-operated haptic device is proposed. Operators who use this haptic device with additional environmental sensing devices can work safely away from the dangerous sites. First, based on the concept design of the haptic device, its workspace is analyzed and the workspace mapping from the haptic device to the excavator is explored. Second, after 7 steps of the excavating processes are defined, the kinematics which deals with the conversion from the 3 dimensional position information of the haptic device to the joint variable information of the backhoe is included in this paper. Lastly, 3D graphical simulation of both haptic device and the backhoe will be shown. This new design of the haptic device can be easily manufactured and gives the workers very convenient and transparent remote control capability.

KEYWORDS

Haptic Device, Excavator, Inverse Kinematics, Dismantling Process

1. INTRODUCTION

Nowadays, there are many construction sites where new skyscrapers are built. Also, re-modeling or dismantling of existing buildings is unavoidable due to the limitation of land. Some methods and/or equipments have been developed for the dismantling processes but they can not sometimes be used due to the size of building and environmental factor. From this reason, mechanical crushing process is still very common method in dismantling sites. Furthermore, equipments that are used in construction sites are usually adapted to dismantle the building. Especially, an excavator equipped with crusher at its end is a good example of the dismantling equipments. However, the dismantling process is very dangerous if operator rides on the excavator at first hand. So, tele-operation system to manage the excavator from remote site is inevitable to assure the operator's safety.

There have been some recent studies related to the tele-operation of the excavator. First, kinematics analysis and simulation of construction devices were conducted by

Frimpong[1]. Furthermore, Frankel[2] studied remote control of excavator with commercial haptic device, Phantom. Finally, haptic device of excavator which was operated in underwater was studied by Hirabayashi [3].

The remote controller, that is, haptic device of excavator for dismantling processes, is the main theme of this paper. The haptic device is designed based on the kinematics of the excavator, which can cover 3-dimensional workspace. Moreover, when the excavator is remotely controlled, the forces exerted to the links and joints of the excavator can be very high but not transferred to the operator, which may result in the damage of the excavator in the extreme case. In order to solve this problem, the remote controller is designed to feedback the force to the operator. In this paper, kinematics analyses of the designed haptic device as well as the excavator are also studied. Based on these analyses, the transformation between the haptic device and the excavator is defined. Finally, 3 dimensional modeling of the excavator and the haptic device by OpenGL program are shown. The models are applied to digging operation through computer simulations.

2. KINEMATICS OF EXCAVATOR

2.1 Kinematics of Excavator for Haptic

There are so many kinds of backhoes in the world but excavator whose joints are represented by 4 motion, swing, boom, arm, and bucket, is chosen in this paper. This excavator can be easily seen in dismantling sites. Based on this motion, Fig. 1 shows that 4 coordinates of each links of the excavator. Swing joint axis of excavator is represented by Z_{e1}, and the remaining three joint axes, boom, arm, bucket are also represented.

After the modeling of excavator, forward and inverse kinematics analysis is also studied. When the haptic devices are designed, the inverse kinematics analysis is more important. Because the operator wants to control the bucket link, the pose of bucket link is determined by the haptic device. So, according to the bucket's pose, four joint angles of excavator are controlled by the inverse kinematics analysis.

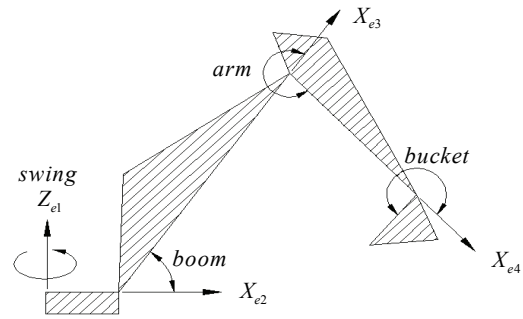


Figure 1 Kinematics Modeling of Excavator

Excavator's degree of freedom is 4, at the same time, bucket can move in 3-dimensional space. So, the bucket movement can be represented with haptic stylus in 3D space. However, when excavator's motion for real digging operations is examined, it is observed that the swing motion is nearly not used. That is, the excavator's main motion is controlled by 3 DOF without swing, which determines the bucket's 2D motion. The swing motion is usually used to move the dug earth to other side. If the swing motion is separated from the digging motion and can be controlled by the haptic device's another reserved joint, operator can control the excavator more easily.

Therefore, inverse kinematics analysis of excavator which is 2-dimensional kinematics problem to control the boom, arm, and bucket will be shown in the next section.

2.2 Kinematics Analysis of Excavator

When the operator is using the haptic device, the angle and position of bucket can be obtained by the absolute position of the haptic stylus. In fact, the angle of bucket and the position of bucket tip are important to control the excavator. However, if the position of a rotational axis of bucket (Z_{e4}) and its angle can be controlled separately from the bucket tip's position and angle, more intuitive controllability can be obtained. So, important point to control the excavator is distal joint position of arm, and this information is used in inverse kinematics analysis. Following equations are inverse kinematics equations to calculate the angles of boom and arm[2].

$$\theta_{e2} = \tan^{-1}\left(\frac{r_{24}(y)}{r_{24}(x)}\right) + \cos^{-1}\left(\frac{a_2^{\,2} + r_{24}^{\,2} - a_3^{\,2}}{2a_2 r_{24}}\right) \quad (1)$$

$$\theta_{e3} = \pi + \cos^{-1}\left(\frac{a_2^{\,2} + a_3^{\,2} - r_{13}^{\,2}}{2a_2 a_3}\right) \quad (2)$$

a_2 : Boom length (distance from Z_{e2} to Z_{e3})
a_3 : Arm length (distance from Z_{e3} to Z_{e4})
r_{24} : Distance from Z_{e2} to Z_{e4}
θ_{ei} : Angle or each link ($i = 1, 2, 3, 4$)

The angle control of bucket is also designed with separate joint from boom and arm control in the haptic device like the swing control in the previous section. Due to simple control method, the bucket is not included in the kinematic analysis.

2.3 Workspace Analysis of Excavator

Fig. 2 shows the workspace of excavator from side view. First, the dual line represents the boom link of excavator whose length is 2m, and the thick line does the arm link whose length is 1.4m. The cross dots represents the trajectory points of distal joint of the boom when the boom joint moves from (-30) to (60) degree. In the figure, the rotational axis of boom is on the point (1m, 1m). And the range of arm angle is from (240) to (360) degree. So, the black little dots represent the area of distal joint of the arm. That is, the rotational axis of the bucket is within this area. In consequence, this area defines the workspace of the excavator.

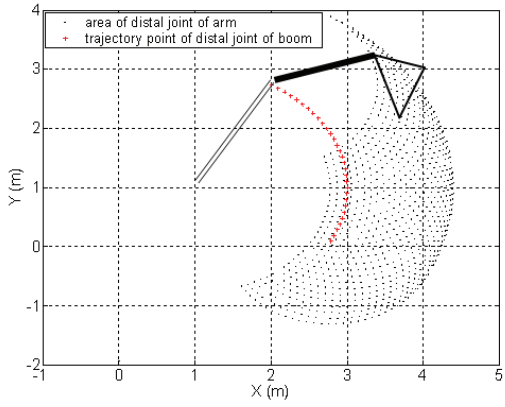


Figure 2 Workspace of Excavator (Joint Position of Arm Link)

3. DESIGN OF HAPTIC DEVICE

3.1 Design Concept of Haptic Device

In this paper, a haptic device is designed, such that operator can work with intuitive bucket control. So, novice operator can use the excavator easily unlike the conventional controller. Fig. 3 shows the conceptul picture of the haptic device. Coordinate assignment is also shown in the figure with Denavit-Hartenberg coordinate system and the used parameter values are defined in Table 1. The degree of freedom is 4 and swing and bucket control is directly connected to two joints of haptic device. For example, θ_{h1} controls the swing motion and θ_{h4} does the bucket motion directly.

The position of arm tip is controlled by θ_{h2} and d_{h3}. Therefore, the angles of boom and arm (θ_{e2} , θ_{e3}) are calculated by inverse kinematics analysis.

Table 1 DH-parameter of haptic device

i	θ_{hi}	α_{hi}	a_{hi}	d_{hi}
2	$\pi/2 + \theta_{h2}$	$-\pi/2$	0	0
3	0	0	0	d_{h3}

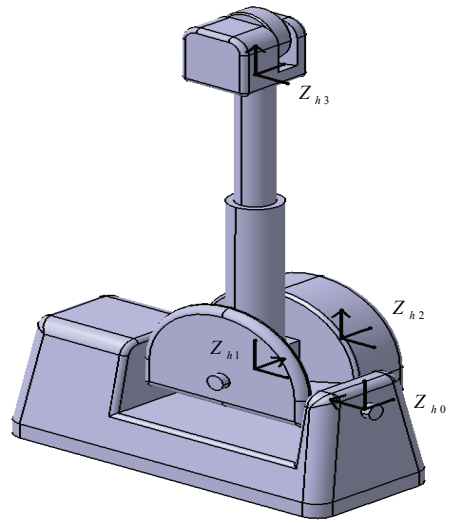


Figure 3 Conceptual design of Haptic Device with D-H Coordinates (only Z axes are shown)

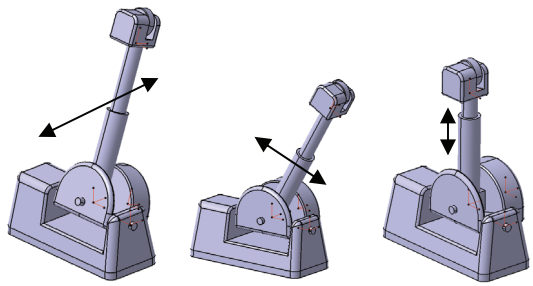


Figure 4 Motion of Haptic Device

Fig. 4 shows how to move the joints of haptic device. Fig. 4 (a) is a picture of swing motion control. Fig. 4 (b), (c) show the control of θ_{h2} and d_{h3} which corresponds to the bucket joint position. This means that operator can move the haptic stylus in 2-D plane and these information are transferred to the excavator to control the θ_{e2} and θ_{e3}, the angles of boom and arm, respectively. Lastly, the force measured at the bucket joint is usually very high, because the bucket is responsible for main operation of excavation or dismantling. Therefore, it is more advantageous for the operator to control the bucket angle by a separate joint like a thumbwheel which is comfortable to operate. This thumbwheel which directly controls θ_{h4} is set up on the haptic stylus.

Fig. 5 shows internal mechanism of the haptic device. There are 4 actuators, electrical motors, and also 4 encoders. The encoders read the angle of each link, and the actuators are used to feedback the forces from the excavator to operator.

3.2 Kinematics Analysis of Haptic Device

To calculate the position vector of the end point of the haptic stylus relative to base frame, transformation matrix T is used like following equation.

$$ {}^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) $$

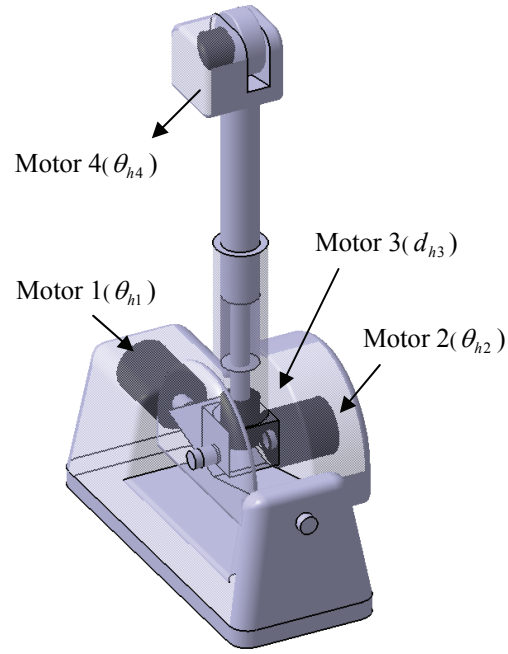


Figure 5 Force Feedback Mechanism of 4 DOF Haptic Device Using Electrical Motors

When the drive mapping between the haptic device and the excavator is defined, θ_{h2} and d_{h3} are control factor to find out the position of bucket rotational axis. So, from the base frame of the haptic to the haptic stylus, transformation matrix is obtained by multiplication of two matrix, ${}^1T_2$ and ${}^2T_3$. DH parameters are already known and these values are the components of the transformation matrix. For forward kinematics of the haptic device, θ_{h2} and d_{h3} are given, and the stylus position should be calculated. It is solved by following equation.

$$ {}^1P = {}^1T_2 \, {}^2T_3 \, {}^3P \quad (4) $$

${}^1P$ is the position vector which represents the stylus position relative to the coordinate 1, ${}^3P$ is also the position vector relative to the coordinate 3. The stylus position is coincident with the origin of the coordinate 3, that is, ${}^3P$ is $(0,0,0,1)^T$. In summary, by using the haptic device, operator can control the whole excavator joints.

3.3 Workspace Analysis of Haptic Device

Fig. 6 is the picture of workspace of haptic device, and this is shown from side view of haptic device. That is, the workspace is calculated from the two parameters, θ_{h2} and d_{h3}. The range of θ_{h2} is from (-50) degree to (50) degree and the range of d_{h3} is from (0) m to (0.3) m. The rotational axis of θ_{h2} is on the point (0m, 0m). Workspace analysis is a initial step to control the excavator with haptic device.

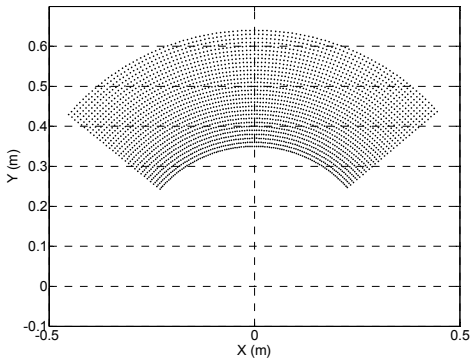


Figure 6 Workspace of Haptic Device

4. MAPPING FROM HAPTIC DEVICE TO EXCAVATOR

Pose information from the haptic stylus position and the angle of thumbwheel controlled by operator decides the angles of excavator joints. In the previous section, the excavator swing motion is controlled by θ_{h1}. If θ_{h1} is minus value, excavator swings left. It turns right otherwise. Next, θ_{e2} and θ_{e3} are controlled by θ_{h2} and d_{h3}. First, the haptic stylus position is read by forward kinematics and these values are converted to the position of bucket joints. This position can be obtained by scaling the workspace between the haptic device and the excavator. Fig. 7 shows the work space mapping from the haptic device to the excavator. In sections 2.3 and 3.3, each workspace is already obtained. Scaling factor 17.5 is used to enlarge the small workspace of the haptic device, and entire workspace is translated on Y-axis by (-7). In the results, the workspace of the haptic device covers that of excavator, so that the haptic device can control the excavator completely. Lastly, the thumbwheel value, θ_{h4}, is directly connected to the bucket angle. This mapping ratio is 1:1, in this paper. However, operator can finely control the bucket by changing this ratio.

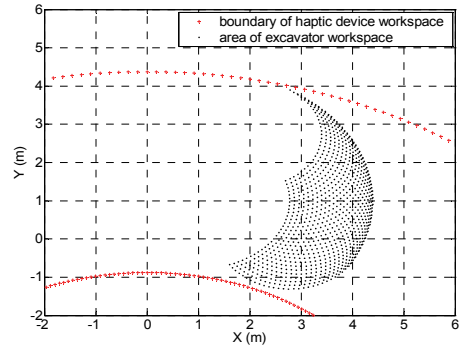


Figure 7 Workspace Mapping From Haptic Device to Excavator

5. SIMULATION RESULTS

In the previous sections, kinematics and workspace analysis of excavator and haptic device are derived. From now, simulation of haptic drive will be shown. Fig. 8 shows the models of the excavator and the haptic device with OpenGL program. OpenGL modeling of haptic device is simple to check the motion of each link. Simulation is applied to digging process and this is composed of 7 sequences like followings.

1. Reach out with the bucket to soil
2. Plunge down into the soil
3. Draw the bucket to fill it with dirt
4. Lift the bucket
5. Swing the bucket over to the spoil pile
6. Unload the bucket onto the spoil pile
7. Swing the bucket back and repeat

Table 2 is the pictures of digging processes in order. In each process, the movement of excavator and haptic device is shown.

This program works in real time. Mouse is used to control the haptic in the computer simulation. 2D position of the mouse represents the 2D position of bucket joint, and thumbwheel is directly used to control the bucket like haptic device. And swing control is carried out by

pushing the arrow keys of keyboard. In Fig. 8, a thumbwheel of haptic is represented like 3rd link instead of one circle like thumbwheel to check the movability. And swing motion controller is cut out, because this joint is not parallel with the other joints.

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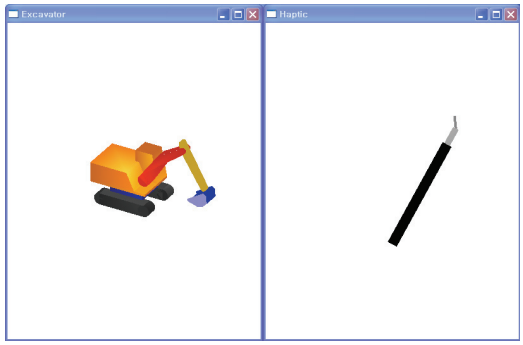


Fig. 8 OpenGL Modeling of Excavator and Haptic

6. CONCLUSION

In this paper, new haptic device was designed to control the excavator. Kinematics and workspace analysis were conducted and OpenGL graphical simulation of the haptic device was also included. As a result, the designed haptic device was proven to be very intuitive and convenient.

7. ACKNOWLEDGMENT

This research was supported by a grant(code:06 Construction Core B04) from Construction Core Technology Program funded by Ministry of Construction & Transportation of Korean government and BK21.

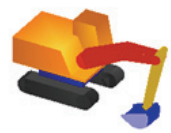
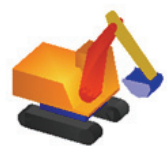
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Table 2 Simulation (Digging Processes)

Process 1	Excavator	Haptic
Process 1		
Process 2		
Process 3		
Process 4		
Process 5		
Process 6		
Process 7	Repeat	

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DETECTION OF DUMP TRUCK FOR LOADING OPERATION BY WHEEL LOADER

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ABSTRACT

The authors have been conducting development of an autonomous loading system by wheel loader. As a part of the development, a detection method of location of the dump truck will be described in this paper. In the process of loading to the truck in the operation, the loader approaches to the dump truck in very close distance. The function for collision avoidance between the loader and the truck is an essential function for the autonomous system. The detection of location of the truck is based on GPS data and Laser Range Finders (LRF). The detection based on LRF is more precise and robust. The developed detecting method is installed and tested on the Experimental loader in test field. The system shows very good results.

KEYWORDS

Wheel Loader, Autonomous System, Loading Operation, Laser Range Finder

1. INTRODUCTION

Earth moving operation is a basic task in fields of construction, mining and so on. Wheel Loader (loader hereinafter) is one of the major loading machines using in those fields. The authors have been conducting a development of an autonomous system for loading operation by wheel loader [1][2]. The developing system is completely self-contained and required no assist of human operator. Localization and detection of other object such as the pile and the truck are essential function for an autonomous system.

Loading operation consists of cycle of phases: (1) scooping from the pile, (2) traveling to the dump truck, (3) loading to the truck and (4) traveling to the pile. In the phase of loading to the truck, the loader approaches to the dump truck in very close distance and the bucket overlaps on the vessel of the truck. The function for collision avoidance between the loader and the truck is important in this phase. A precise and robust detection system is required.

2. DEVELOPING WHOLE SYSTEM

The most common loading method by wheel loader is V-shape method as in Fig.1. The loading operation is carried out by repetition of the cycle with four phases described in previous section.

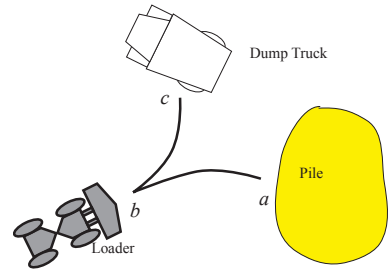


Figure 1 V-Shape Loading Method

The developing system is installed on the experimental loader: Yamazumi No.4 (YZ4) as

shown in Fig.2. YZ4 is about 7m in length and about 7ton in weight. Hydraulic system is arranged for computer control with pilot valves. PCs and sensors are mounted for following functions. The autonomous system consists of the planning sub-system, the motion control sub-system and sensor system. The planning sub-system makes decision for scooping point, V-shape path and loading point to the dump truck. The planning sub-system for scooping point issues the scooping position and direction on the edge of the pile based on the position and shape of the pile. The planning sub-system for loading point issues the loading position and direction on the vessel of the truck. The path planning sub-system generates a path between the scooping point and the loading point. Because the Scooping points and the loading point are changed with advancing of the operation cycle by cycle, the planning procedure is executed for each cycle of the operation.



Figure 2 YZ4 and Experimental Dump Truck

The sensor system is classified in two categories: the inner sensors and the outer sensors. The inner sensors detect a mechanical state of the loader including angles of steering, arm, bucket and wheel. The outer sensors detect the environment including the position and direction of the loader by GPS system, the position and shape of the pile by stereo-vision system and the distance between the loader and the truck by Laser Range Finder (LRF).

3. TRACK DETECTING SYSTEM

In the experiment, GPS positioning system is installed on the experimental dump truck. YM4 and the experimental truck can communicate with each other through LAN. Therefore YZ4 knows the position and direction of the truck with accuracy of GPS positioning. GPS antennas of YZ4 are attached on the roof of cockpit and the height from the ground is about 4m. Tyres are deformed by weight of scooped material in the bucket. The position of antennas is affected by this tyre deformation up to about 0.2m in horizontal direction. In the process of loading, distance between the tip of bucket and the vessel of the truck is less than 0.5m. The position error of GPS antenna is not negligible and other sensing system with high accuracy is required.



Figure 3 LRF on YZ4

For this propose, two scan type LRF are attached on the front part of YZ4 as shown in Fig.3. As LRF emits laser beam and scan in a plane, a cross sectional shape of objects in the scanning plane is detected. Usually LRF is set in direction making the scanning plane horizontal however LRF are attached in direction which gives vertical scanning plane for the truck detection. Two LRF are attached with a bar at both side of the front part of YZ4. Attached positions are out side of the bucket slightly. The position of the bucket does not affect sensing of LRF. The maximum measuring range is set at 80 m with 10mm resolution. The scanning range is 180 degrees and the emittion interval is 0.5 degree. One set of scan data includes 361 data. The interval time of the scan is about 30Hz. In Fig.4, an example of a set of data is shown.

4. ALGORITHM FOR DETECTION

One set of data includes cross sectional shape of the truck including the vessel, the ground and other thing such as tyre of the truck. For detection of the vessel, corresponding part in the whole data should be identified. The algorithm for identify or elimination is describe below.

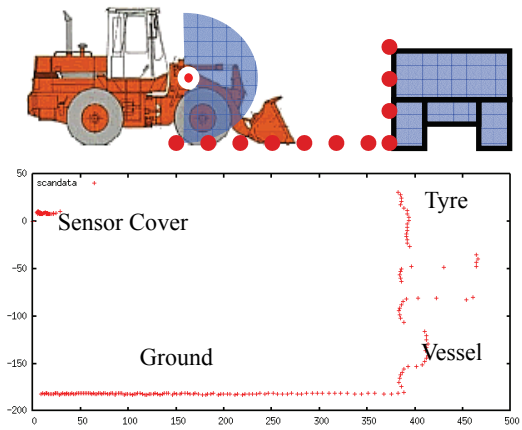


Figure 4 An Example of Set of Data

The first step is an identification of the ground. A part of the data which locates beneath the sensor can be assumed the ground with very high probability. A fitting line to a part of the data beneath LRF is drawn by the method of least square. Neighboring points of the fitting line are supposed as the ground. The rest of the points represent the truck including the vessel, the tyre and other structure.

The second step is identification of the upper end point of the vessel. During loading phase, the bucket should clear the upper end of the vessel for collision avoidance. As the side wall of the vessel is vertical, the corresponding data to the vessel make a series of point on vertical straight line. To find out the series of data, Ransac (Random Sample Consensus) method is applied. The procedure of the identification of the upper end point is as follows:

(1) Choose a certain amount of the data at random from the data representing the truck. Draw a line fitting to the chosen points by method of least square.

(2) Points whose distance to the line obtained in (1) is less than a threshold are selected as neighboring points to the line. Count the number of the neighboring points N. Then draw a line fitting to these points by the least square method again. Calculate a mean and variance of distance between each point and the line.

(3) Repeat the procedure (1)-(2) several times. Then select a set of data with the largest N and the least variance as the set representing the vessel of the truck. The highest point in the set is selected as the upper end point if the vessel.

5. EXPERIMENTAL RESULTS

Fig.5 and Fig.6 show an example of the results and the procedure. Fig.5 is the result of the identification of the ground. The data with range of 1m to 1.2m from LRF is used for the fitting. The fitting line is drawn in Fig.6. Points within 0.2m range from the line in upper and lower side are supposed to be the ground and the rest is supposed to be the data corresponding to the truck. The ground part is identified very clearly by this method.

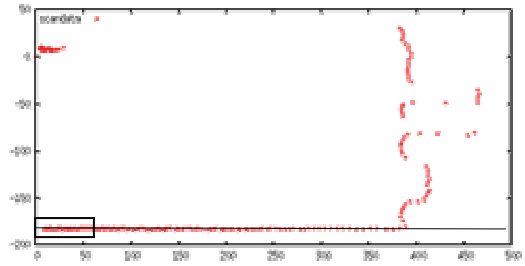
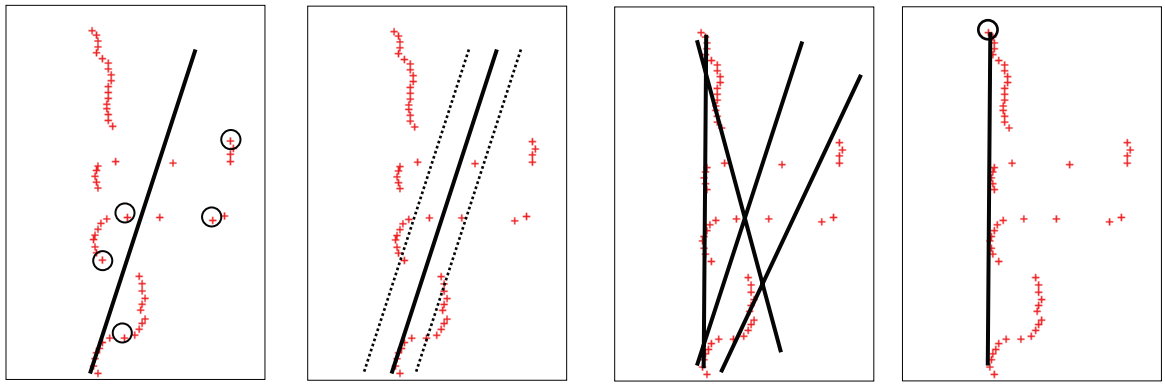


Figure 5 Identification of Ground

Fig.6 illustrates the result of the procedure (1)-(3). Fig.(a) shows the fitting line to chosen points. The amount of chosen points is 20% of the points without eliminate as the ground. Usually the total number of the point is approximately 25 to 100 and it changes by the distance between LRF and the truck. In Fig(b), the threshold lines of distance from the fitting line are drawn. The threshold distance is 0.12m. Fig(c) shows repetition of procedure (1)-(2). The number of the repetition is 50. Finally, a line with the largest number of the including points and the least variance is selected as the set represents the vessel of the truck. The highest point in the set is supposed to be the upper end point of the vessel (Fig(d)). It is clear that the most suitable point is selected as the upper end point.



Fig(a) Random Points and Fiting Line

Fig(b) Threshold Lines

Fig(c) Repetition 50 cycles

Fig(d) Final Result

Figure 6 Example of Results

6. CONCLUSIONS

As a part of development of an autonomous system for loading operation by wheel loader, detecting method of the truck by LRF is developed. The developed detecting system is installed and tested on experimental loader TZ4.The results show that the developed system can detect the truck very precisely. It works very well even in heavy rain condition.

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COORDINATION STRATEGY FOR PATH PLANNING OF MULTIPLE MANIPULATORS IN WORKCELL ENVIRONMENT

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ABSTRACT

In this paper, a coordination strategy for determining collision free path of end effectors of two manipulators involved in coordinated manipulation is proposed. This strategy consists of collision checking and path planning modules. Collision checking is done by modeling the links and environment of manipulator using sphere swept volume technique and utilizing minimum distance heuristic for interference check. Path planning is based on a two step approach for which breadth first search, A* algorithm and incremental A* algorithms are used to search the optimal collision free path. While determining the path of the end effector of manipulators, the obstacles present in the work space are considered as static obstacles and the links of the manipulator are viewed as dynamic obstacles by the other manipulator. The proposed coordination strategy is demonstrated by considering two manipulators with 6 degrees of freedom operating in 3D work cell environment with certain static obstacles.

KEYWORDS

Coordination Strategy, Multiple Manipulators, Collision Checking, Incremental Search

1. INTRODUCTION

Industrial manipulators/robots are employed for a wide range of applications wherein a single or multiple robots assist the execution of tasks in a work cell environment. These tasks can range from very simple pick and place to a precise assembly tasks. In case of certain assembly tasks such as spot welding of an automobile body, multiple manipulators are needed. Moreover, these manipulators have to be activated simultaneously to perform the tasks in a desirable manner. In order to utilize these manipulators for any specified task, it is essential to plan the sequence of movements of each manipulator in the work space with the consideration of obstacles and objects. This basically involves path planning and trajectory planning. Many attempts were made towards path planning and trajectory planning of single manipulator. Limited attempts were made to generate the path and trajectory for multiple manipulators considering their operation in cooperative and coordinated mode. Coordinated motion planning of multiple manipulators assumes considerable significance in case of precision assembly and manufacturing tasks carried out with multiple manipulators. Attempts made on multiple manipulator coordinated manipulation are essentially directed towards collision free trajectory planning. Some attempts made in this direction include (i) leader follower strategy wherein the movements of one manipulator have priority over the movements of other manipulator [1], (ii) time delay strategy wherein the motion of one manipulator is delayed by minimum time to avoid possible collision with other robots [2], and (iii) speed alteration strategy in which the speed of the links of one manipulator is made different from the speed of various links of other manipulator in order to avoid any collision with it [3]. All these approaches are based on the assumption that the environment is static, well known apriori and

focus on the trajectory for collision free task execution. Hence, they are mostly suited for online planning and execution of tasks in coordinated manipulation. As this process hinders the utility of manipulators and requires enormous time for trajectory planning, there exists a need to look at methods that can generate the path for coordinated manipulation in offline mode. This approach can help in offline generation of path for coordinated motion of manipulators i.e. path planning which in turn can be utilized for trajectory generation and execution with any specific controller with minimal effort and time. In order to develop such an approach for offline generation of path for coordinated motion of manipulators, it is necessary to consider the movement of links of one manipulator with respect to the links of other manipulator as varying with time, thus making the environment dynamic due to the varying position of links of the manipulators in the task performance. Thus, the present work attempts to focus on the development of coordination strategy for path planning of multiple manipulators. This strategy essentially requires the determination of collision free space and planning the path for multiple manipulators coordinating task while considering the links of manipulators as dynamic obstacles. Collision free space determination essentially demands the modeling of work space and interference checking between interacting entities. Among the various techniques available for modeling, oriented bounding boxes [4] and minimum volume ellipsoid [5] techniques are commonly used to model the links of manipulator and environment. Since these techniques are computationally complex and time consuming, swept sphere volume technique (SSV) is found to be the most effective and accurate technique for modeling the links of manipulator and the environment [6], [7]. Collision free configuration space can be found by performing the interference check among the interacting elements of workspace using different methods like minimum distance heuristic, overlap of geometries etc. Path planning essentially deals with the determination of optimal collision free path for executing the task. For this purpose, several approaches can be found in the literature. Out of them, probabilistic roadmap approach and grid search techniques are the most popular. But, if the environment is dynamically changing like in multiple manipulator workcell environment, the most widely used probabilistic roadmap approach (lazy PRM) may fail as the movement of obstacle will lead to elimination of roadmap edges [8]. On the other hand, grid search technique poses certain difficulties like increase in complexity of search in exponential manner with an increase in dimension of configuration space. Attempts made to reduce the complexity of search include the reduction in the number of neighboring nodes to be searched with a heuristic combined with grid search technique [9], incremental building of grids in higher dimensional spaces based on random sampling [10] and incremental version of A* to reduce the number of nodes to be recomputed by reusing the information from previous searches [11]. All these approaches can be employed to obtain the path for manipulators with both static and dynamic obstacles. In the present work, a new strategy is proposed to generate collision free path that can ensure the avoidance of collision of manipulator with static as well as dynamic obstacles. The proposed strategy attempts to utilize SSV for modeling of various links of manipulators, obstacles and objects, minimum distance heuristic for interference checking and collision avoidance with an incremental A* approach for obtaining an optimal path for coordinated manipulation.

2. OUTLINE OF PROPOSED APPROACH

In figure 1, strategy proposed for coordinated manipulation is outlined. The proposed strategy is a two step approach in which the path for coordinated manipulation is generated with a coupled interaction between collision checking and path planning module. In the first step, collision checking module aids in determining collision free configuration space for each manipulator with respect to static obstacles and the path planning module determines an optimal collision free path for achieving the desired task among the static obstacles only. In the second step, the collision free path determined in previous step i.e. various configurations of first manipulator are checked for any mutual collision with moving links of second manipulator. In this process, the links of other manipulators are considered as dynamic obstacles. If collision occurs, the configurations are removed from the collision free configuration space of the

manipulator. The remaining collision free space is used to replan the path considering both static and dynamic obstacles. This replanning makes use of both the steps of path planning. By this procedure, replanning is continued until the collision free configurations are found for both manipulators. The proposed strategy essentially includes the tasks outlined in following modules.

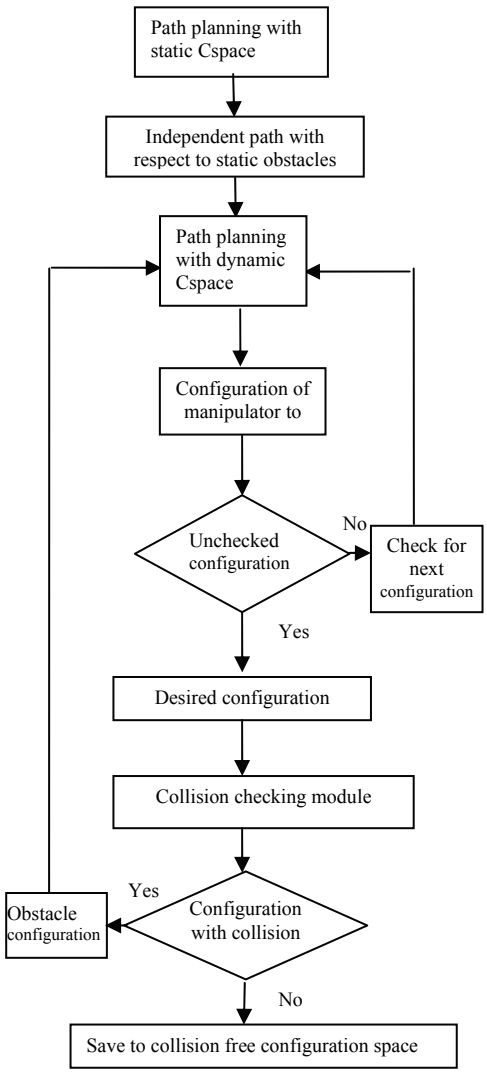


Figure 1 Strategy for Coordinated Manipulation

1. Collision checking module
   a) Modeling of manipulator links and obstacles using sphere swept volume (SSV)
   b) Checking the interference among various geometric primitives modeled using SSV
   c) Determination of collision free configuration space.

2. Path planning module
   a) Determination of collision free path for each manipulator considering only static obstacles
   b) Determination of collision free path for coordinated manipulation with static and dynamic obstacles in position

3. COLLISION CHECKING AND PATH PLANNING

3.1 Collision Checking

The collision checking involves modeling of links of manipulator and obstacles in the environment using SSV, interference checking using the minimum distance heuristic and the determination of collision free Cspace.

3.1.1 Robot link modeling using sphere swept volume (SSV) technique

SSV is a sphere that is swept out along geometric primitives such as point, line and rectangle. It results in a sphere around a point, cylinder with hemispherical ends around a line and a block with rounded edges and corners around a rectangle (Figure 2). These volumes provide means for varying the shape of bounding primitive to achieve a tighter fit to underlined geometry. The link of manipulator is modeled as a cylinder with hemispherical ends. The complex shaped obstacles are enclosed in spherical volume and obstacles with rectangular cross section are modeled as platform with rounded edges and corners. The interference between links of manipulator and static or dynamic obstacles is determined by using minimum distance heuristic. The minimum distance among different geometric primitives is determined by using computational geometry concepts [12]. If this minimum distance is less than the specified value, then interference occurs among primitives under study. This particular configuration of manipulator is considered as collision configuration.

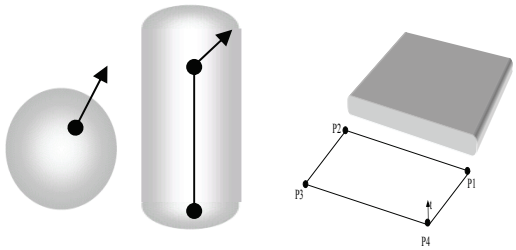


Figure 2 Geometry of Solid Obtained by Sphere Swept Volume for (a) point (b) line (c) rectangle

3.1.2 Determination of Cartesian Configuration Space (C space)

In order to analyze the motion of manipulator end effector for coordinated task Cartesian coordinate frames are assigned to each link to transform joint angles into task space coordinates. The task space coordinates are nothing but the position and orientation of the end effector with respect to reference base frame. The relative position and orientation of coordinate frames of two adjacent links is expressed in terms of transformation matrices defined as follows:

$$ {}^{i}A_{i-1}=\begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

i = 1,2,3…n, where n is the number of links and a_i, α_i, θ_i, d_i are link length, twist angle, joint angle and joint offset variables respectively. Joint angles of the manipulator θ_1 to θ_6 are varied by a unit degree within the range of angles specified by kinematic constraint of manipulator, to generate manipulator configurations in terms of $[\theta_1,\theta_2,\theta_3,\theta_4,\theta_5,\theta_6]$. These configurations are given as input to collision checking module to ensure them to be collision free and then subjected to singularity check. Singularities are those manipulator configurations for which robot transitorily loses one or more degrees of freedom. The singularities occur at manipulator configuration for which the determinant of Jacobian matrix is zero. Hence, Jacobian matrix for each manipulator is determined. The manipulator configuration which gives the determinant of Jacobian matrix as zero is eliminated though it is collision free. Then these collision free, non singular joint angle configurations $[\theta_1,\theta_2,\theta_3,\theta_4,\theta_5,\theta_6]$ are substituted in transformation matrices and are converted into Cartesian variables [x, y, z]. All such collision free singularity free configurations forms a Cartesian Cspace which is then used for determining the path using path planning approach proposed in the next section.

3.2 Path Planning

As discussed earlier, path planning is carried out in two steps. In the first step, collision free Cartesian Cspace of manipulator with respect to static obstacles is obtained by means of collision checking module. This Cspace is searched for optimal collision free path using breadth first search (BFS) and A* algorithms. These are very widely used grid search algorithms especially suited for obtaining optimal path in static search space. BFS carries out exhaustive search of the Cspace and visits almost all the nodes in the Cspace to find optimal path. In contrast to this, A* algorithm uses heuristic to calculate the cost of movement in the Cspace and then to guide the search. This search is faster than BFS since less number of nodes are used for search. In the second step, the collision free path of manipulator determined in previous step is executed and checked for any mutual collision with links of second manipulator as they become dynamic obstacles for the manipulator under consideration. If these configurations are not collision free, these configurations are removed and collision free Cspace is updated. This updated collision free space is considered to replan the path considering the static and dynamic obstacles. Replanning of path is done by using an incremental A* algorithm [11]. It reuses information gathered in previous searches and hence effective for replanning purpose. The process of replanning is continued till optimal collision free is found with consideration to static and dynamic obstacles. In order to highlight the effectiveness of incremental A* algorithm, replanning is also done by using BFS and A* algorithm.

4. SIMULATION EXAMPLE

In order to illustrate the application of the proposed coordination strategy, two identical Kuka Kr industrial manipulators with 6 rotary joints are

considered for coordinated manipulation. Table 1 presents Denavit Hartenberg parameters of real size Kuka Kr manipulator.

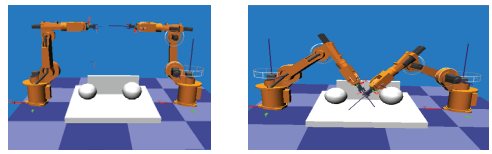
Table 1 Denavit Hartenberg Parameters [13]

Link	θi	αi	ai	di	Joint angle range
1	θ_1	+90	280	715	-180^O to 150^O
2	θ_2	0	615	0	-30^O to -55^O
3	θ_3	+90	0	0	-60^O to -210^O
4	θ_4	+90	0	540	-270^O to 90^O
5	θ_5	+90	0	0	-300^O to 54^O
6	θ_6	0	0	0	-360^O to 310^O

In the workcell, there are two manipulators with two spheres and one rectangular block as obstacle. The initial and final configuration for manipulators are selected in such a way that these manipulators will definitely collide during their movement from initial configuration (Figure 3(a)) to final configuration (Figure 3(b)).

5. RESULTS AND DISCUSSION

The proposed coordination strategy utilized SSV technique for modeling of the links of manipulator and environment since it requires minimum geometric information of manipulator links or obstacles. This technique facilitates easy computation of distance heuristic which in turn speeded up the collision checking process. The collision free configurations are transformed to Cartesian coordinates using transformation matrices. This collision free Cartesian Cspace is searched for optimal collision free path using various search algorithms. The results obtained with various search algorithms employed in the proposed strategy are shown in Table 2. Figure 4 shows the initial path (i.e. optimal collision free path with respect to static obstacles only) and final path (i.e. optimal collision free path with respect to static as well as dynamic obstacles) of both the manipulators. From the results presented in Table 2, it can be seen that there is vast difference in number of nodes searched by BFS and A* algorithm.



(a) (b)

Figure 3 Coordinated Task with 2 Manipulators (a) Initial Configuration (b) Final Configuration

Table 2 Results Obtained With Different Path Planning Algorithms

Search algorithm	Robot	No. of nodes searched to determine initial path (step1)	No. of nodes searched to determine final path (step2)	Replanning cycles
BFS	R1	163	146	20
	R2	165	144	26
A*	R1	6	3	7
	R2	5	4	15
Incremental A*	R1	6*	6	5
	R2	5*	6	7

This can be attributed to the exhaustive search carried out by BFS which involves the search of almost all nodes of the Cspace for finding an optimal path. On contrary, A* algorithm is a guided search with a heuristic that has reduced the number of nodes searched in the process. The initial path obtained by BFS and A* is given in the figure 4(a) for both robots. Incremental A* algorithm uses the path generated by A* algorithm as initial path for each robot. Thus the number of nodes searched by this algorithm is the same as that of A* algorithm (6* nodes and 5*nodes) to obtain the initial path. To obtain the final path (i.e. collision free path with respect to static as well as dynamic obstacles) for coordinated task, replanning is required. The final path obtained by BFS and A* algorithm is given in figure 4(b) and that obtained by incremental A* algorithm in figure 4(c) for both the manipulators. Since BFS and A* search techniques are one time computation algorithms which reconstruct a new path every time the state of the environment changes, they require more number of replanning cycles. In contrast to this, incremental A* algorithm works on reuse strategy than a replan strategy and reconstructs only the areas affected by the changes to the state of environment.

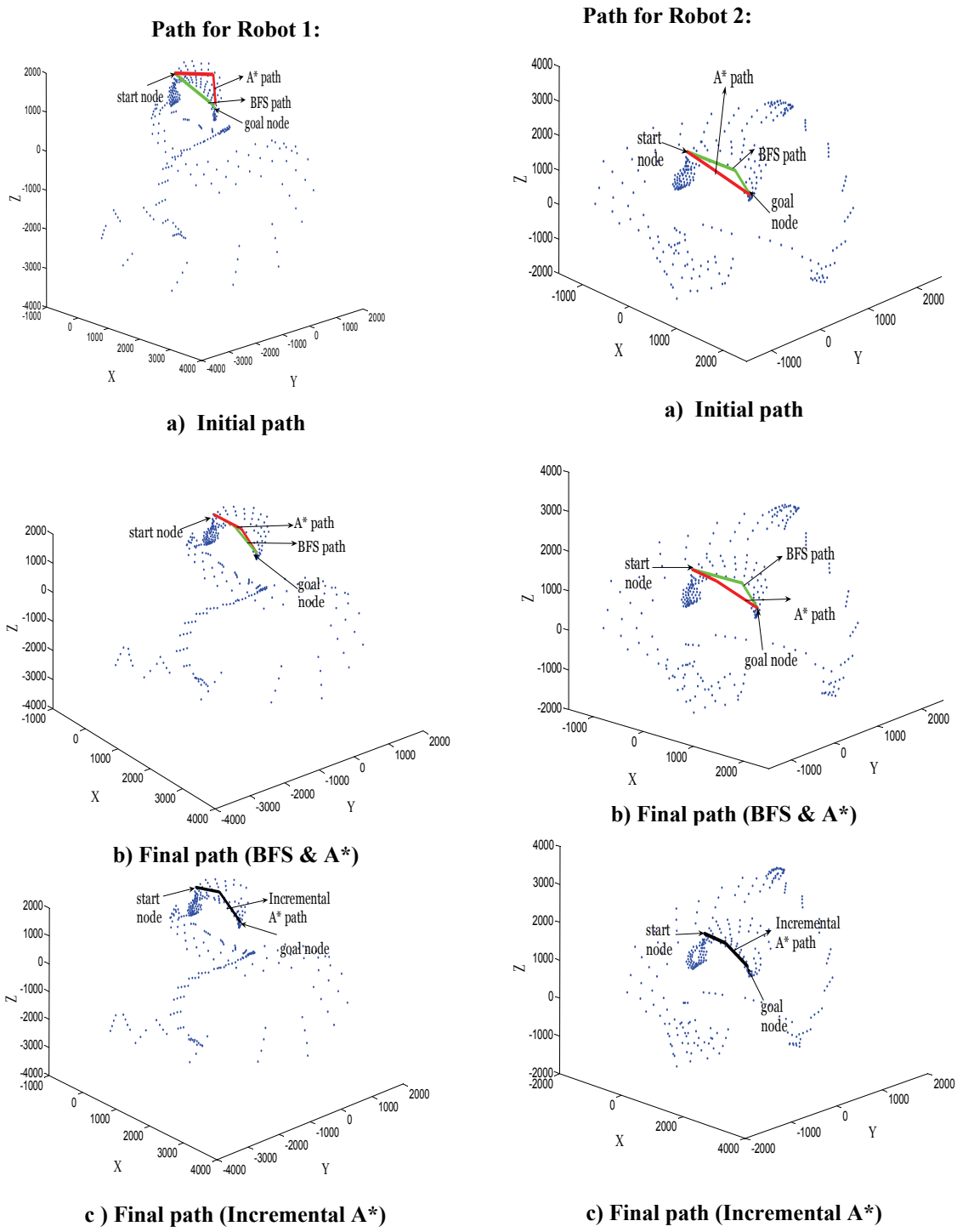


Figure 4: Collision Free Paths Generated for Robot 1 and Robot 2 using BFS, A* and Incremental A* Algorithms

It generates the initial path using A* algorithm and uses it for further replanning so as to obtain the final path.

6. CONCLUSIONS

The proposed coordination strategy for collision free path planning of multiple manipulators made use of SSV technique for modeling of links of manipulators and obstacles, minimum distance heuristic as interference checking criterion and a two step approach for path planning with A* and incremental A* algorithms as search algorithms. Path planning approach is unique in a way that the collision free path for each manipulator is determined by considering the obstacles in the workspace as static obstacles and the collision free path for coordinated manipulation is obtained by considering the links of interacting manipulators as dynamic obstacles. Incremental A* algorithm chosen for coordinated path planning is found to reduce the number of replanning cycles substantially thus showing its promise for path planning of manipulators with dynamic obstacles. Though the proposed strategy considered the coordinated path planning of two manipulators with certain geometry of obstacles, it is capable of generating the collision free path for more than two i.e. multiple manipulators considering different geometry of obstacles.

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COLLABORATIVE AGENT-BASED SYSTEM FOR MULTIPLE CRANE OPERATION

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ABSTRACT

Operating cranes in a construction project should meet several requirements of capacity, safety and spatial constraints. Much research has been done about selecting cranes, simulating the work processes, training operators and optimizing working paths to improve the efficiency and reduce conflicts in real construction operations. However, most of the research focused on equipment working individually rather than coordinating multiple works, such as the case of two cranes working together to lift a heavy or large object. The complexity of coordinating equipment requires more detailed planning and better real-time control of the work. The present paper proposes a new approach using artificial intelligent agents to enhance communication between two cranes and resolve distributed problems in the construction industry. A framework is developed to simulate the working environment of two cranes on site. A simulation model is under development using a case study to investigate the feasibility of the proposed approach.

KEYWORDS

Collaborative Agents, Crane Operation, Simulation

1. INTRODUCTION

Most of the materials and components in a construction project are lifted by cranes. It is estimated that one crane upset occurs during every 10,000 hours of crane use. Nearly 80% of these upsets can be attributed to predictable human error when the operator inadvertently exceeds the crane's lifting capacity [1].

Much research has been done about selecting cranes, simulating the work processes, training operators and optimizing working paths to improve the efficiency and reduce conflicts in real construction operations. Commercial software is available for crane selection and path planning [2, 3]. The advantage of visualizing the work is that the user can simulate and check the functional constraints and interferences that may happen in reality between the 3D physical elements and virtual workspaces. However, these simulation tools focus on equipment working individually rather than coordinating the work of several cranes, such as the case of two cranes working together to lift a heavy or large object. The complexity of coordinating equipment requires more detailed planning and better real-time control of the work. Ali et al. [4] have proposed a path planning approach using a Genetic Algorithm (GA) for automating the path planning of two cooperative construction manipulators. Artificial intelligence (AI) research aiming at the creation of unmanned construction systems, capable of performing complex tasks as well as human operators, has been carried out to control construction work on hazardous sites or for space and underwater constructions. These systems have been applied to perform emergency countermeasure and restoration work at disaster sites [5]. It is mentioned that the efficiency of unmanned construction is roughly 60-70% of that of manned

construction, but sharply decreases in cases where the machinery moves or high precision work is necessary [5]. For example, collaborative equipment work is a common case in construction where communication and negotiation are essential to properly accomplish the work. Some research involving AI has been done to enhance communication between team workers and resolve problems in the construction industry. The concept of agents in AI refers to relatively independent and autonomous entities, which operate within communities in accordance with complex modes of cooperation, conflict and competition in order to survive and perpetuate themselves [6]. Using agents to plan and coordinate construction activities can simulate the manoeuvring of the equipment and enhance communication to reduce conflicts and improve efficiency. Agent systems have been used for construction claims negotiation [7] and dynamic rescheduling negotiation between subcontractors [8]. However, little research has focused on real-time control for construction equipment operation using agents. Furthermore, activities may need to be carried out in a multi-equipment environment to achieve a specific goal, such as two cranes working together to lift heavy or big objects. Multiple agents can be used to simulate such type of collaborative work. The distributed organization is able to adapt more easily to unforeseen modifications in the environment and, in particular, to possible malfunctions of certain agents [9]. In some cases, re-planning is needed to avoid obstacles that were not considered in the original plan. Once this happens, communication between operators is essential to exchange information and generate new actions based on the individual's knowledge. Multi-agents are able to interactively simulate such kind of re-planning based on negotiation.

In the present paper, a new approach based on collaborative agents is proposed to coordinate construction equipment operation. A multi-agent framework is developed to simulate the working environment of two cranes on site. A simulation model is under development using a case study to investigate the feasibility of the proposed approach. Compared with the previous research for cranes path planning, this method enhances the real-time control based on the perception of the environment.

2. FRAMEWORK

2.1 Framework Structure

Figure 1 shows the framework of an agent-based system for collaborative cranes. Many agents are involved to plan the path and guide the two cranes to finish the task on the worksite. Agents have separate but interdependent tasks to meet their final objective and to carry their work. Every agent has basic functionalities of sending and receiving messages, and decision making. Three major agents are involved: *Crane Agent A*, *Crane Agent B*, and *Site State Agent*.

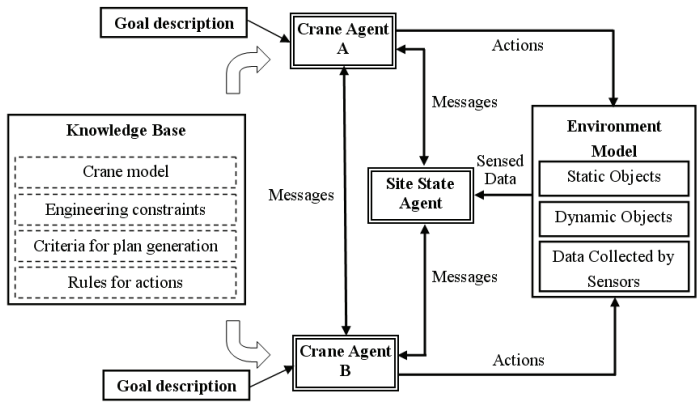


Figure 1 Framework of an Agent-based System

2.1.1 Crane agent

A *Crane Agent* has several low-level agents working together to communicate, detect the position of the crane and plan the path. As shown in Figure 2, the *State Receiver* gets information from sensors about the components' position, such as the boom length, boom swing angle, and other parameters necessary to describe the states of the crane; then, it extracts and transfers data to the *Path Planner*, which is responsible for path planning based on searching possible movement of the crane. The *Controller* is responsible for getting information from the knowledge base and other agents and extracting and transferring data to the *Path Planner*. The information obtained from other agents shows the states of the other crane and the worksite environment, such as whether there is an obstacle on the moving path of the cranes. The *Path Planner* will read the goal descriptions and search the possible path according to predefined rules to avoid the obstacles and meet the constraints imposed either from the engineering or safety aspects. The path decided by the *Path Planner* is sent to the *Controller* to check with the other *Crane Agent* and revise the plan if necessary. After a final path is decided, the *Path Planner* sends the actions to the *Operator*, which translates the actions to lower level actions that can be understood by the crane operator on the site or to automatically operate the crane.

2.1.2 Site state agent

The *Site State Agent* is responsible for collecting states from the crane agents and the work site environment model, including both static and dynamic information. Static information includes geometric, kinematic, and static information of all system components. Most of the previous research has been focusing on path planning with assumptions of the site containing static obstructions [10]. The present work tries to enhance the communication by collecting information from the dynamic world. Therefore, knowing the position of each part of the boom and detecting any obstacle on the moving path is essential to ensure that the work is done properly while meeting the kinematics and engineering requirements. Different sensors can be used to either report the position of the crane [11] or to detect the collisions in real time [12].

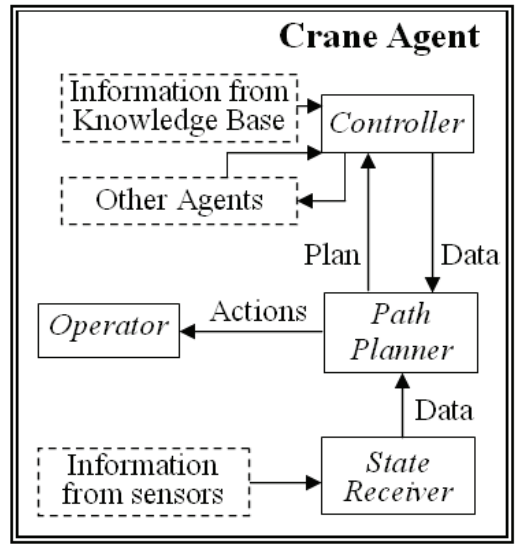


Figure 2 Crane Agent Hierarchy

2.1.3 Knowledge Base

The *Knowledge Base* includes four parts: crane model, engineering constraints, criteria for plan generation, and rules for actions. The crane model has the kinematic constraints for the selected cranes. A loaded crane has a maximum of eight degrees of freedom (DoFs), and path planning for manipulators having more than four DoFs is considered to be complex [13]. The scope of the present work is limited to four DoFs, as shown in Figure 3. The engineering constraints of cranes are mainly from the working range and the load charts. The working range shows the minimum and maximum boom angle according to the length of the boom and the counterweight. Load charts give the lifting capacity based on the boom length, boom angel to the ground and the counterweight. Three major criteria should be taken into account: Lift path clearances, capacity during lift, and ground support during lift. Rules should be developed to represent these constraints which are stored in a database. One important rule is that the distance between two hooks should be equal to the length of the lifted object, and crane load lines must be kept plumb at all times for multiple crane lift [14]. Other rules include avoiding combinations of hoisting and swinging or hoisting and luffing at the same time; and avoiding boom's motion when a crane is traveling.

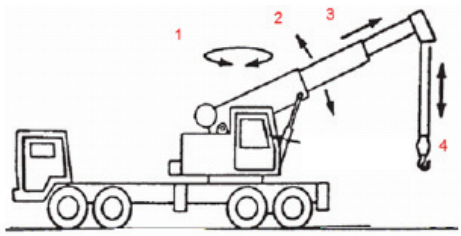


Figure 3 DoFs of a Crane

2.2 Communication between Agents

When several agents are working together, it is necessary to define the relationships between their actions to improve the coordination of these actions and reduce conflicts. Communication between agents is essential for arranging the behaviors of the agents in time and space, which basically requires exchanging messages between agents. KQML (Knowledge Query and Manipulation Language) [15] provides a framework for agents to exchange information and knowledge. It defines the operations that agents may attempt on each other's knowledge bases and provides a basic architecture for agents to share knowledge and information. The messages transferred between crane agents and the *Site State Agent* follow the KQML format (Figure 1). One agent can simply *accept* or *reject* the proposed action from other agents to achieve a shared plan through these messages.

2.3 Collaboration between Agents

Coordination-by-planning technique is the most traditional approach in AI, which is based on breaking the work down into two phases. In the first phase (planning), a set of plans are produced including a set of actions to be carried out by agents. The selection of a correct representation of actions becomes even more crucial than in the planning for a single agent [9]. In the second phase (executing), one plan is selected and then executed. Due to the dynamic environment, re-planning may be needed, which requires real-time information updating and searching a new path based on this information.

3. COMPUTING ASPECTS

Properly represented information is important to avoid complex computation and improve the knowledge acquisition. Parameters are defined to describe the goals, actions and the states. These facts can be used to fire specific rules defined in the Knowledge Base to generate new facts and guide further actions.

3.1 Representation of Goals

The goal of the crane operation can be simply represented by two points related to the load object: origin and destination. Origin (ob, P_o, Φ_o) represents the original position P_o and orientation Φ_o of the object ob. P_o (x_o, y_o, z_o) is given by the coordinates of the reference point of ob. Destination (ob, P_d, Φ_d) represents the destination position P_d and the orientation Φ_d of ob. Duration (t_1, t_2) represents the start time t_1 and the end time t_2 of the work.

3.2 Representation of Actions

Different movements of a crane can be decomposed into a series of actions. Taking a hydraulic crane as an example, the movement of the crane includes the following actions:

Base movement: BaseMove, BaseStop;

Boom movement: BoomRaise, BoomLower, BoomExtend, BoomRetract, BoomSwing;

Hook movement: HookHoist, HookLower, HookStop, HookGrip, HookRelease.

3.3 States Description

States representation is based on the actions taken before. For example, at State j:

ObjectLocation (ob_k, P_{kj}, Φ_{kj}): object ob_k is at position P_{kj} with orientation Φ_{kj};

CraneLocation ($crane_i$, P_{ij}, Φ_{ij}, θ_{ij}, α_{ij}, l_{ij}, P^{h}_{ij}): crane i is at location P_{ij}, with base orientation Φ_{ij}, boom swing angle θ_{ij}, boom angle to the ground α_{ij}, boom length l_{ij}, and hook position P^{h}_{ij};

HookGrip ($crane_i$, ob_k): the hook of $crane_i$ is gripping ob_k;

Distance ($hook_i$, $hook_{i+1}$, d_j): the distance between two hooks is d_j;

3.4 Plan Generation

Generating a plan may be seen as a state space search. Most implementations of search algorithms

should be assisted by appropriate domain heuristics to find a good/optimal path within a reasonable time [16]. As discussed in the previous section, the kinematic motion requirements and engineering constraints are integrated to generate reasonable plans for each crane. The whole plan can be divided into tasks which consist of sub-tasks or a set of crane actions. Three major tasks category can be defined as: pre-lift task, lifting task, and post-lift task. The pre-lift task includes the actions for positioning the cranes on site and attaching the load to the hook; the lifting task, which is the main body of the work; and the post-lift task, which includes detaching the load and moving to another place. The lifting task combines several sub-tasks, which indicates the milestones on the moving path. These milestones can be used as the target when re-planning is needed to reduce the search time. Each task is fulfilled by taking actions to change the states of the crane. The study of Varghese et al. [17] has shown that no industry-wide standard for heavy lift planning practices exists at present. The experts rely primarily on experience to develop the plans or to perform optimization. Furthermore, collaborative requirements also limit the possible movement of each crane, which reduces the actions that can be taken by agents. In one scenario, one crane agent is given the priority to generate the actions and the partial plans to move the object lifting half of its weight. The other crane agent can follow by taking reactive actions or reject the actions due to its own constraints. Rules are used to check the feasibility of each action. The priorities of an agent may change according to specific rules. Through negotiation, an effective plan can be generated based on possible combinations of movements of cranes from one step to another.

4. CASE STUDY

The re-decking project of Jacques Cartier Bridge in Montreal is used to demonstrate the proposed collaborative agent-based system. The deck of this bridge was replaced during 2001-2002. The existing deck was cut by saw into sections. Each section was removed by two telescopic cranes and a new panel was installed using the same cranes. Figure 4 shows two telescopic cranes lifting a panel.

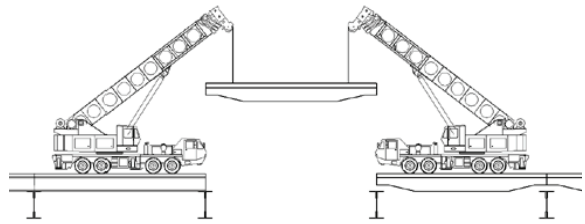


Figure 4 Two Cranes Lifting a Panel [18]

The contractor built a physical model of a part of the bridge and different types of cranes to check the feasibility and to plan the movement of each crane. In the real lifting situation, the operators were guided by a coordinator to ensure the safety and to guide the operations. By repeating the same tasks, the productivity was improved from 1 panel to 6 panels per night. Figure 5 shows the schematic representation of two cranes working together to lift an old section and load it on a trailer.

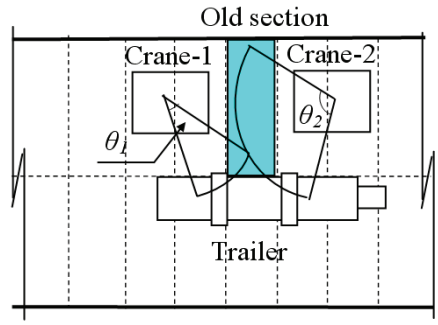


Figure 5 Swing Ranges for Two Cranes

The task shown here can be described by changing only the swing angles of the cranes (θ_1 and θ_2). One possible plan to synchronize the movement of the boom of the two cranes is to define the unit movement of the cranes as θ_1/T and θ_2/T, respectively (T is the duration of the task). A simulation model is under development using Java language to create a virtual environment including the work site, the bridge structure and two virtual cranes. Transformation matrices are used to specify the relative location of each component of the cranes with respect to its parent. Load charts and working ranges are retrieved from a database to control the cranes' movement. A preliminary test is under development to facilitate the communication between two agents representing the two cranes.

5. CONCLUSIONS

This paper described a framework of multi-agent system for collaborative cranes on construction site. Agents are used to plan and execute the work on site by communicating with each other and making decisions for actions based on negotiation. Computing aspects are discussed for representing the goal, actions, and states and for path planning. A simulation model is under development using a case study about a bridge rehabilitation project where two cranes were working together to lift a panel with a height constraint from the bridge structure. The preliminary test shows the feasibility of the proposed approach. Future work will focus on further developing and testing the system. -

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A GENERIC FRAMEWORK FOR CONTROLLING BI-HANDED ROBOTIC MANIPULATORS

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ABSTRACT

From design to implementation, bi-handed humanoid manipulators are more complex than common industrial robots. Humanoid manipulators have the properties of redundancy and bifurcation, which enable placement of multiple hands or tools at desired positions and orientations within the robot's workspace in an unlimited number of ways. To address and benefit from these complexities, Energid Technologies has developed a generic XML-based control method supporting virtually any number of degrees of freedom, any type of end-effector constraint, any type of joint, and any optimization criterion for fixed and mobile robots. This paper will address how this technology works, the problems it solves, its ongoing application as a software toolkit accessible to the robotics community.

KEYWORDS

Branching Robot, Kinematics, Control, Simulation

1. INTRODUCTION

Robots have had a presence in constructional engineering for decades. Today, robots are contributing to the production of goods through applications such as semi automated earthmoving, material handling, and assembly [1]. Robotic systems not only help in improving productivity, but also make it possible to work in hazardous environments and extreme situations (such as during natural-calamities).

Recently, humanoid robots have risen in prominence, and these have potential to stand in for human workers in a variety of construction-related activities [1]. The control of humanoid robots is challenging, however. As the application of robotics in construction increases, it becomes important to look into a common control method to suit changing robotic shapes and configurations.

2. COMMON SOFTWARE FRAMEWORK

The robot-control framework we describe here incorporates the kinematic, dynamic, and physical-extent properties of the manipulator components, and it allows flexible specification of velocity control algorithms in a language based on the Extensible Markup Language (XML). This

framework can control and simulate any number of cooperating manipulators. The primary requirement for controlling a manipulator is knowledge of its kinematic and dynamic properties.

3. THE LINK-BASED MODEL

A bi-handed manipulator is represented in software through a tree/branching structure topology as shown in Figure 1 below.

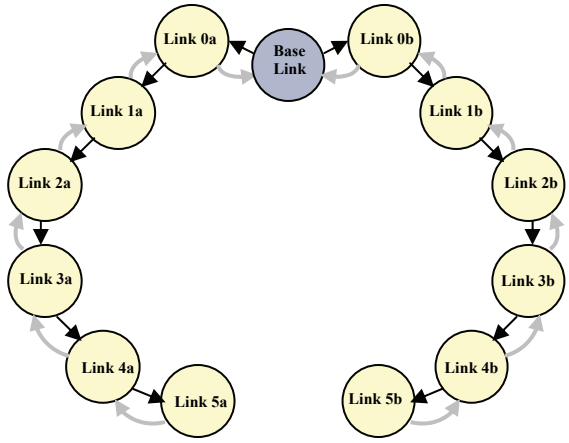


Figure 1 Manipulator Link Model

The manipulator is composed of links in a branching structure, where each link moves relative to its parent in the tree. Programmatically, each link has access to all of its children and to its parent.

With this established topology, the burden of defining the manipulator is equivalent to defining each of the individual links.

4. LINK KINEMATICS AND DYNAMICS

The link model uses three reference frames. The proximal D-H frame, as we will call it, is rigidly attached to the parent. The distal D-H frame aligns with the proximal D-H frame of the children. The rigid body describing the link moves with respect to the distal D-H frame of its parent when the joint value of the link changes. Each link also has a special frame, the primary frame. The primary frame is rigidly attached to the distal D-H frame, but with a fixed offset. It is used to define link properties such as mass and physical extent. It is also used as a reference when defining end effectors. These frames are illustrated in Figure 2 below.

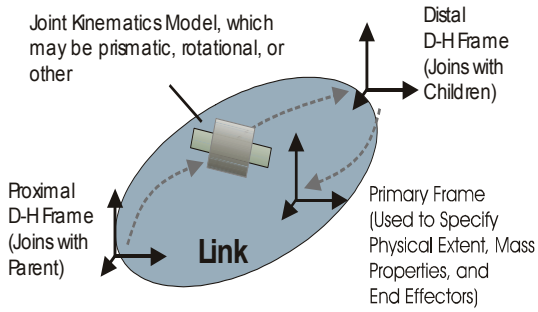


Figure 2 The Link Reference Frames

The proximal and distal D-H frames are so named because they correspond to the Denavit-Hartenberg (D-H) frames when this formalism is used for describing the joints

Energid's toolkit supports the two most common D-H approaches, as found in robotics textbooks. The first is Paul's Denavit-Hartenberg notation [2], which uses the kinematic sequence {z-rotation, z-translation, x-rotation, x-translation}. The second is Craig's notation [3], using the kinematic sequence {x-rotation, x-translation, z-rotation, z-translation}.

In addition to the Denavit-Hartenberg representation, support is included for general axes of rotation and translation. These options allow utmost flexibility in describing links with rotational or prismatic joints. Listing 1 below shows part of the XML description for the Cyton A7D-1G (Energid's humanoid manipulator) configuration.

This representation of robot link information is conceptually different from the traditional representation. Traditionally, robotic links are connected with joints—that is, the links lie between the joints. In this formulation, the link conceptually contains the joint. The distal frame of one link is rigidly attached to the proximal frame of a child. This provides a more flexible way to represent kinematic properties. It allows multiple formalisms (such as Paul or Craig's Denavit-Hartenberg notation) to be used internally to the link. It also supports the representation of new types of joints.

Listing 1 XML from the Cyton A7D-1G Arm Description

```
  <mn:linkKinematicsContainer>
- <mn:denavitHartenberg>
  <mn:a>0</mn:a>
  <mn:alpha>0</mn:alpha>
  <mn:d>0</mn:d>
  <mn:dhType>generalPaul</mn:dhType>
  <mn:jointType>rotational</mn:jointType>
- <mn:precursor>
  <mn:orient q0="1" q1="0" q2="0" q3="0"
      />
  <mn:translation x="0" y="0" z="0" />
     </mn:precursor>
- <mn:primaryFrame>
  <mn:orient q0="1" q1="0" q2="0" q3="0"
      />
  <mn:translation x="0" y="0" z="0" />
     </mn:primaryFrame>
  <mn:theta>0</mn:theta>
     </mn:denavitHartenberg>
   <mn:firstMoment x="0" y="0" z="0" />
  <mn:mass>1.180</mn:mass>
- <mn:secondMoment>
  <mn:jXX>0.02</mn:jXX>
  <mn:jXY>0</mn:jXY>
  <mn:jXZ>0</mn:jXZ>
  <mn:jYY>0.01</mn:jYY>
  <mn:jYZ>0</mn:jYZ>
  <mn:jZZ>0.01</mn:jZZ>
     </mn:secondMoment>
     </mn:massProperties>
- <mn:shapeContainer>
- <mn:trianglePhysicalExtent>
  <mn:bypassDynamics>0</mn:bypassDynami
      cs>
  <mn:canDeform>0</mn:canDeform>
  <mn:deformable>0</mn:deformable>
  <mn:detailLevel>3</mn:detailLevel>
```

To describe link kinematics (position, velocity, and acceleration), the algorithm supports general joint types with one degree of freedom. Thus, not only are rotational and prismatic joints supported, but also screw-type joints, motion along a rail, and any other type of motion that can be parameterized by a scalar.

5. CORE ALGORITHMIC FRAMEWORK

Once a robotic mechanism is defined as described in the previous section, the generic software framework is capable of implementing and exchanging a variety of velocity control algorithms for all types of kinematically redundant, bifurcating manipulators.

The core velocity framework is based on the manipulator Jacobian equation:

$$\mathbf{V} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}. \tag{1}$$

Here, $\mathbf{V}$ is an m-length vector representation of the motion of one or more hands (usually some combination of linear and angular velocity referenced to points rigidly attached to parts of the manipulator); $\mathbf{q}$ is the n-length vector of joint positions (with $\dot{\mathbf{q}}$ being its time derivative); and $\mathbf{J}$ is the $m \times n$ manipulator Jacobian, a function of $\mathbf{q}$. For traditional industrial robots, $\mathbf{V}$ is often formed by combining the linear and angular velocity of a single tool or hand. A key point for bi-handed humanoid manipulators is that $\mathbf{V}$ takes on a larger meaning—it includes the concatenation of point, frame, or other motion of multiple end-effectors.) This is illustrated in Figure 3 below.

Figure 3 shows Energid's Cyton A14D-2G, 14DOF humanoid Bi-handed manipulator, and the illustration of the parameters for velocity control. The column vector V represents the combined motion of both hands (for positioning and orienting both hands, it would be 12×1), and $\mathbf{q}$ represents the concatenated joint values (14×1). The Jacobian $\mathbf{J}(\mathbf{q})$ is the matrix that makes (1) true for all possible values of $\dot{\mathbf{q}}$. Note in the toolkit $\mathbf{V}$ can represent a concatenation of other types of end-effectors as well.

For any physical manipulator that is not self-connecting, a manipulator Jacobian can be defined to make equation (1) true. When the manipulator is kinematically redundant, the dimension of $\mathbf{V}$ is less than the dimension of q ($m<n$), and (1) is underconstrained when $\mathbf{V}$ is specified. By using V to represent relative motion, (1) can also support self-connecting mechanisms by setting the relative motion to zero.

The velocity control question, then, is the following: given a desired hand motion V, what are the joint rates $\dot{\mathbf{q}}$ that best achieve this motion? To answer this, the framework is built on a method which uses a scalar α, a general column vector $\mathbf{F}(\mathbf{q})$, and a matrix function to solve for $\dot{\mathbf{q}}$ given $\mathbf{V}$ through the following formula:

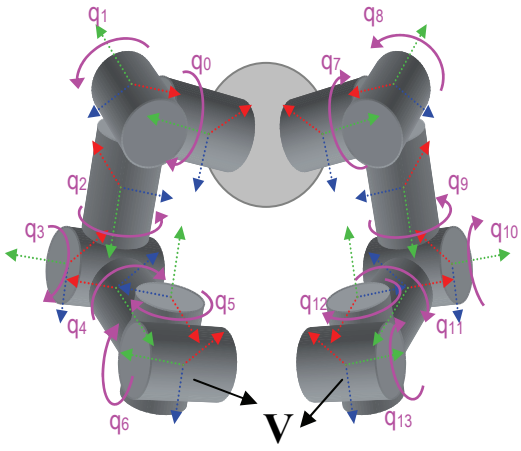


Figure 3 Configuration of Cyton A14D-2G

$$\dot{\mathbf{q}} = \begin{bmatrix} \mathbf{J} \\ \mathbf{N}_\mathbf{J}^T \mathbf{W} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{V} \\ -\alpha \mathbf{N}_\mathbf{J}^T \mathbf{F} \end{bmatrix}. \quad (2)$$

where $\mathbf{N_J}$ is an $n \times (n–m)$ set of vectors that spans the null space of $\mathbf{J}$. That is, $\mathbf{JN_J} = 0$, and $\mathbf{N_J}$ has rank $(n–m)$. $\mathbf{N_J}$ is generally a function of $\mathbf{q}$. By changing the values of α, $\mathbf{W}$, and f, many new and most established velocity-control techniques can be implemented [4].

Equation (2) is the core velocity-control algorithm used by the frame work. Mathematically, it achieves the desired $\mathbf{V}$ while minimizing $\frac{1}{2}\dot{\mathbf{q}}^T \mathbf{W} \dot{\mathbf{q}} + \alpha \mathbf{F}^T \dot{\mathbf{q}}$. The parameters α, $\mathbf{W}$ and $\mathbf{F}$ can be defined using XML to give many different types of velocity control, including pseudoinverse control [5], weighted pseudoinverse control [6], augmented Jacobian techniques [7], [8], extended Jacobian techniques [9], [10], and projection methods [11], [12].

6. LOCAL POSITION CONTROL

The local position control uses the following procedure: The current pose of an end-effector (for example location or location and orientation for point and frame end effectors, respectively) and the desired pose are used to construct an end-effector velocity that, if followed, will give alignment.

For point end effectors, the desired velocity of the point is simply a scalar gain times the difference in position. That is, if $\vec{p}_a$ is the actual position and $\vec{p}_d$ is the desired position (both with respect to the system frame), then the desired velocity, $\vec{v}_d$, is given by the following, where k_ℓ is a user-specified positive gain.

$$\vec{v}_d = k_\ell \cdot (\vec{p}_d - \vec{p}_a). \quad (3)$$

The similar calculation for three-dimensional frames is more complicated. For this, the velocity is calculated as specified in equation (3) and in addition an angular velocity is calculated as a vector proportional to the minimum rotational angle needed to align the actual orientation with the desired orientation. Every orientation can be expressed as an axis of rotation and an angle of rotation about that axis. For the rotation between the actual and the desired frame, let this axis be $\hat{u}$ (having unit norm) and let the angle of rotation be θ. Then the desired angular velocity is given by the following, where k_a is a user-specified positive gain:

$$\vec{\omega}_d = k_a \cdot \theta \cdot \hat{u}. \quad (4)$$

In the framework, the angular and linear velocities calculated through (3) and (4) are also capped at a user-defined threshold. The points used in calculating (3) are specified through a user-defined offset. In simulation or for path finding, the actual hand position and orientation values are calculated using ground truth, but in a feedback-based fielded application, they are calculated from sensed joint positions or found directly using visual or other sensors.

7. EXAMPLE

As one example of the type of manipulator that can be controlled using Energid's framework, Figure 4 shows NASA's Robonaut manipulator. This is a robot that can be used for construction, albeit in space. The real robot is shown at the top and a simulated version being controlled and simulated is shown below. This model has 57 degrees of freedom in motion, including two 7-dof arms, two 19-dof hands, a 3-dof waist, and a 2-dof neck and

head. The method described in this paper can be used to control this in real time on a laptop PC.

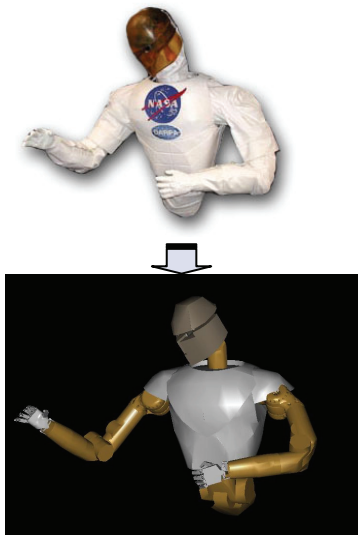


Figure 4 Simulation of Robonaut

Figure 4 shows the result of simulation done for NASA's Robonaut, a bi-handed space-based construction and repair robot with 57 degrees of freedom in motion.

8. CONCLUSIONS

A comprehensive and generic method to control virtually any type of bi-handed robotic mechanisms has been presented. This technology has direct application to robots used to support construction, with its rich diversity of tasks. The proposed method supports single and cooperating robots and the selection of end effectors and tools according to the type of material handled or job performed.

The proposed approach supports the optimization of secondary criteria, such as collision avoidance that enables robotic operation in dynamic work environments. It also supports remote control for hazardous or remote missions. The framework is ideal for automating construction and support operations.

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A MULTICRITERIA APPROACH FOR THE OPTIMAL DESIGN OF 2 DOF PARALLEL ROBOTS USED IN CONSTRUCTION APPLICATIONS

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ABSTRACT

Parallel robots have been used in a large number of applications ranging from astronomy to flight simulators and are becoming increasingly popular in the field of construction industry. This paper is aimed at presenting a study on the optimization of the BIGLIDE and BIPOD parallel robots, which comprises two-degree-of-freedom (DOF) parallel robots with constant and variable struts. The robot workspace is characterized and the inverse kinematics equation is obtained. In the paper, design optimization is implemented with Genetic Algorithms (GA) for optimization considering transmission quality index, design space and workspace. Here, intended to show the advantages of using the GA, we applied it to a multicriteria optimization problem of 2 DOF parallel robots. Genetic algorithms (GA) are so far generally the best and most robust kind of evolutionary algorithms. A GA has a number of advantages. It can quickly scan a vast solution set. Bad proposals do not affect the end solution negatively as they are simply discarded. The obtained results have shown that the use of GA in such kind of optimization problem enhances the quality of the optimization outcome, providing a better and more realistic support for the decision maker. Considering its high load capacity and geometrical dexterity, the system is appropriate for maintenance, building construction, and cleaning of large and dangerous structures.

KEYWORDS

Optimal Design, Parallel Robots, Genetic Algorithms

1. INTRODUCTION

Several papers have dealt with parallel robots to optimize performances [14]. However, many of these are limited to only one performance optimization. For example, various methods to determine workspace of a parallel robot have been proposed using geometric or numerical approaches. Early investigations of robot workspace were reported by Gosselin [1], Merlet [2], Kumar and Waldron [3], Tsai and Soni [4], Gupta and Roth [5], Sugimoto and Duffy [6],Gupta [7], and Davidson and Hunt [8]. The consideration of joint limits in the study of the robot workspaces was presented by Delmas and Bidard (1995). Other works that have dealt with robot workspace are reported by Agrawal [9], Gosselin and Angeles [10], Cecarelli [11]. Agrawal [12] determined the workspace of in-parallel manipulator system using a different concept namely, when a point is at its workspace boundary, it does not have a velocity component along the outward normal to the boundary. Configurations are determined in which the velocity of the end-effector satisfies this property. Pernkopf and Husty [13] presented an algorithm to compute the reachable workspace of a spatial

Stewart Gough-Platform with planar base and platform (SGPP) taking into account active and passive joint limits. Stan [14] presented a genetic algorithm approach for multi-criteria optimization of PKM. Most of the numerical methods to determine workspace of parallel manipulators rest on the discretization of the pose parameters in order to determine the workspace boundary [15, 16]. Other authors proposed to determine the workspace by using optimization [14]. Numerical methods for determining the workspace of the parallel robots have been developed in the recent years. Exact computation of the workspace and its boundary is of significant importance because of its impact on robot design, robot placement in an environment, and robot dexterity.

The objective of this paper is to propose an optimization method for planar mini parallel robots that combines performance evaluation criteria related to the following robot characteristics: workspace, design space and transmission quality index. Furthermore, a genetic algorithm is proposed as the principle optimization tool. The success of this type of algorithm for parallel robots optimization has been demonstrated in various papers [14].

2. DOF MINI PARALLEL ROBOTS

Geometrical description of the parallel robots

Two general planar mini parallel robots with two degrees of freedom activated by prismatic joints are shown in Fig. 1 and Fig. 2.

There are a wide range of parallel robots that have been developed but they can be divided into two main groups:

- Type 1) parallel robots with variable length struts;
- Type 2) parallel robots with constant length struts;

Kinematic analysis

Robot kinematics deal with the study of the robot motion as constrained by the geometry of the links. Typically, the study of the robot kinematics is divided into two parts, inverse kinematics and forward (or direct) kinematics.

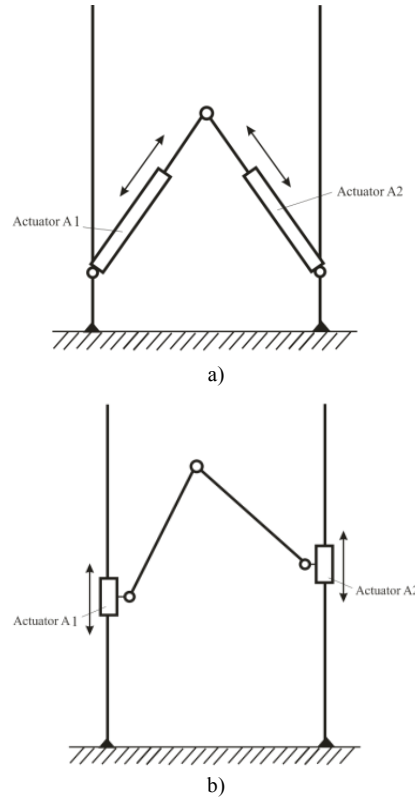


Figure 1.a) Variable Length Struts Parallel Robot b) Constant Length Struts Parallel Robot

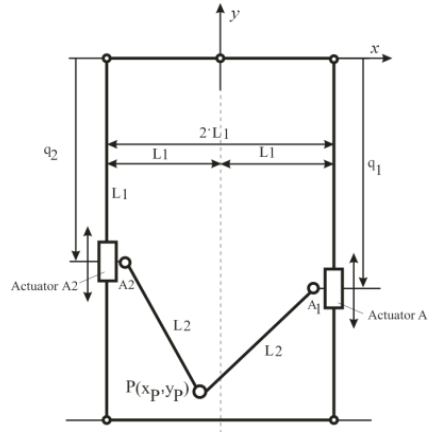


Figure 2 The General Kinematic Scheme of a PRRRP Mini Parallel Robot

The kinematics relation between **x** and **q** of these 2 DOF mini parallel robots can be expressed solving the following equation: f(**x**, **q**) =0.

Then the inverse kinematics problem of the parallel robot from Fig. 2 a) can be solved by writing the following equations:

$$q_1 = y_P \pm \sqrt{L_2^2 - (x_p - L_1)^2}\ ;$$
$$q_2 = y_P \pm \sqrt{L_2^2 - (x_p + L_1)^2} \quad (1)$$

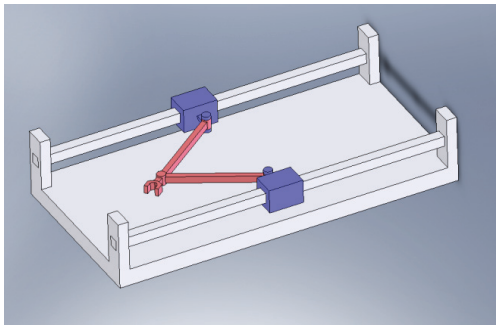


Figure 3 CAD Model of the Parallel Robot

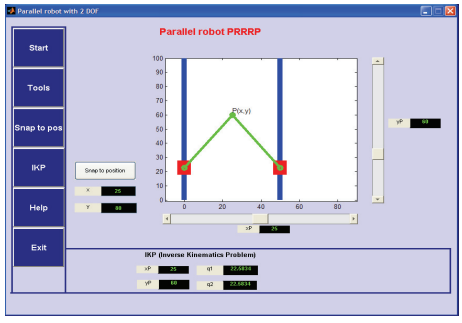


Figure 4 Robot Configuration for X_P=25 mm Y_P=60 mm

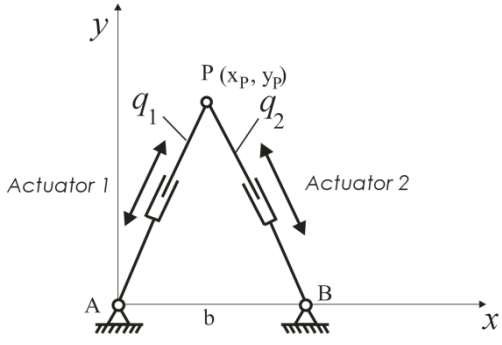


Figure 5 The General Kinematic Scheme of a RPRPR Mini Parallel Robot

Then the inverse kinematics problem of the parallel robot from Fig. 2 b) can be solved by writing the following equations:

$$q_1 = \sqrt{x_P^2 + y_P^2}\ ; q_2 = \sqrt{(b - x_P)^2 + y_P^2} \quad (2)$$

The forward and the inverse kinematics problems were solved under the MATLAB environment and it contains a user friendly graphical interface.

3. WORKSPACE DETERMINATION AND OPTIMIZATION

Workspace evaluation

The workspace is one of the most important kinematics properties of manipulators, even by practical viewpoint because of its impact on manipulator design and location in a workcell [17]. A general numerical evaluation of the workspace can be deduced by formulating a suitable binary representation of a cross-section in the taskspace. Other authors proposed to determine the workspace by using optimization [14].

The following presents the main factors affecting workspace. For ease of comparison a cubic working envelope with a common contour length is used together with a machine size that is calculated from the maximum required strut length.

The working envelope with variable and constant length struts

In this section, the workspace of the proposed robots will be discussed systematically. It is very important to analyze the area and the shape of workspace for parameters given robot in the context of industrial application. The workspace is primarily limited by the boundary of solvability of inverse kinematics. Then the workspace is limited by the reachable extent of drives and joints, occurrence of singularities and by the link and platform collisions. The mechanisms PRRRP and RPRPR realize a wide workspace as well as high-speed. Analysis, visualization of workspace is an important aspect of performance analysis. A numerical algorithm to generate reachable workspace of parallel manipulators is introduced.

Optimization results for RPRPR mini parallel robot

The design of the robot can be made based on any particular criterion. The paper presents a genetic algorithm approach for workspace optimization of Bipod mini robot. For simplicity of the optimization calculus a symmetric design of the structure was chosen. In order to choose the robot dimensions b, q_{1min}, q_{1max}, q_{2min}, q_{2max}, we need to define a performance index to be maximized. The chosen performance index is W (workspace) and T (transmission quality index). An objective function is defined and used in optimization. It is noted as in Eq. (2), and corresponds to the optimal workspace and transmission quality index. We can formalize our design optimization problem as the following:

$$ObjFun=W+T \tag{3}$$

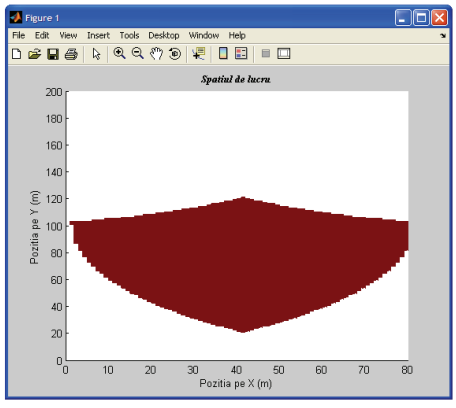


Figure 6 Workspace for the Planar 2 DOF Mini Parallel

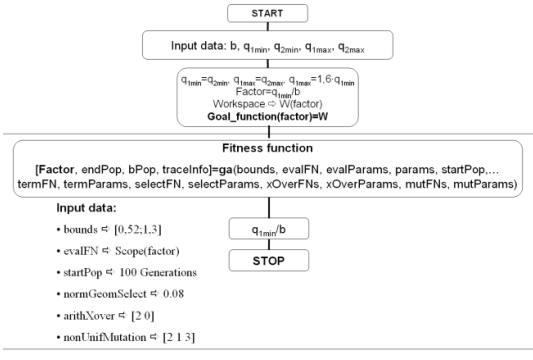


Figure 7 Flowchart of the Optimization Algorithm with GAOT (Genetic Algorithm Optimization Toolbox)

Optimization problem is formulated as follows: the objective is to evaluate optimal link lengths which maximize (3). The design variables or the optimization factor is the ratios of the minimum link lengths to the base link length b, and they are defined by:

$$q_{1min}/b \tag{4}$$

Constraints to the design variables are:

$$0,52<q_{1min}/b<1,35 \tag{5}$$

$$q_{1min}=q_{2min},\quad q_{1max}=q_{2max},\quad q_{1max}=1,6q_{1min},\quad q_{2max}=1,6q_{2min} \tag{6}$$

For this example the lower limit of the constraint was chosen to fulfill the condition $q_{1min}\geq$b/2 that means the minimum stroke of the actuators to have a value greater than the half of the distance between them in order to have a workspace only in the upper region. For simplicity of the optimization calculus the upper bound was chosen $q_{1min}\leq$1,35b. During optimization process using genetic algorithm it was used the following GA parameters, presented in Table 1. A genetic algorithm (GA) is used because its robustness and good convergence properties. The GA approach has the clear advantage over conventional optimization approaches in that it allows a number of solutions to be examined in a single design cycle. The traditional methods searches optimal points from point to point, and are easy to fall into local optimal point. Using a population size of 50, the GA was run for 100 generations. A list of the best 50 individuals was continually maintained during the execution of the GA, allowing the final selection of solution to be made from the best structures found by the GA over all generations.

Table 1 GA Parameters

Generations	100
Crossover rate	0.08
Mutation rate	0.005
Population	50

We performed a kinematic optimization in such a way to maximize the objective function. It is noticed that optimization result for Bipod when the maximum workspace of the 2 DOF planar parallel robot is obtained for $q_{1\min}/b$=1,35. The used dimensions for the 2 DOF parallel robot were: q_{1min}=80 mm, q_{1max}=130 mm, q_{2min}=80 mm,

q_{2max}=130 mm, b=60 mm. Maximum workspace of the mini parallel robot was found to be W= 4693,33 mm^2.There have been obtained different values of the parameter optimization (q_1/b) for different objective functions. The following table presents the results of optimization for different goal functions. W_1 and W_2 are the weight factors.

If an elitist GA is used, the best individual of the previous generation is kept and compared to the best individual of the new one. If the performance of the previous generation's best individual is found to be superior, it is passed on to the next generation instead of the current best individual

Table 2 Results of Optimization for Different Goal Functions

	Method	GAOT Toolbox MATLAB
Goal functions	$Z=W_1 \cdot T+W_2 \cdot W$, $W_1=0,7$ and $W_2=0,3$	q_1/b = 0.92
	$Z=W1 \cdot T+W2 \cdot W$, $W_1=0,3$ and $W_2=0,7$	q_1/b= 1.13
	$Z= W_1 \cdot T$, $W_1=1$ and $W_2=0$	q_1/b=0.71
	$Z=W_2 \cdot W$, $W_1=0$ and $W_2=1$	q_1/b=1.3

The results show that GA can determine the architectural parameters of the robot that provide an optimized workspace. Since the workspace of a parallel robot is far from being intuitive, the method developed should be very useful as a design tool.

Table 3 Results of Optimization for Different Goal Functions

	Method	GAOT Toolbox MATLAB
Goal functions	$Z=W_1 \cdot T+W_2 \cdot W$, $W_1=0,7$ and $W_2=0,3$	*L2* = 1.1
	$Z=W_1 \cdot T+W_2 \cdot W$, $W_1=0,3$ and $W_2=0,7$	*L2*= 1.1556
	$Z= W_1 \cdot T$, $W_1=1$ and $W_2=0$	*L2*=1
	$Z=W_2 \cdot W$, $W_1=0$ and $W_2=1$	*L2*=1.2

However, in practice, optimization of the robot geometrical parameters should not be performed only in terms of workspace maximization. Some parts of the workspace are more useful considering a specific application. Indeed, the advantage of a bigger workspace can be completely lost if it leads to new collision in parts of it which are absolutely needed in the application. However, it's not the case of the presented structure.

Optimization results for PRRRP mini parallel robot

An objective function is defined and used in optimization. Objective function contains workspace and transmission quality index. Optimization parameter was chosen as the link length L2. The constraints was established as 1<L2<1.2. After performing the optimization the following results were obtained:

Based on the presented optimization methodology we can conclude that the optimum design and performance evaluation of the mini parallel robot is the key issue for an efficient use of mini parallel robots. This is a very complex task and in this paper was proposed a framework for the optimum design considering basic characteristics of workspace, singularities and isotropy.

4. CONCLUSION

The fundamental guidelines for genetic algorithm to optimal design of micro parallel robots have been introduced. It is concluded that with three basic generators selection, crossover and mutation genetic algorithm could search the optimum solution or near-optimal solution to a complex optimization problem of micro parallel robots. In the paper, design optimization is implemented with Genetic Algorithms (GA) for optimization considering transmission quality index, design space and workspace. Genetic algorithms (GA) are so far generally the best and most robust kind of evolutionary algorithms. A GA has a number of advantages. It can quickly scan a vast solution set. Bad proposals do not affect the end solution negatively as they are simply discarded. The obtained results have shown that the use of GA in such kind of optimization problem enhances the quality of the optimization outcome, providing a better and more realistic support for the decision maker. Considering its high load capacity and geometrical dexterity, the system is appropriate for maintenance, building construction, and cleaning of large and dangerous structures.

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COOPERATIVE TASK PLANNING OF MULTI-ROBOT SYSTEMS

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ABSTRACT

Multiple cooperating robots hold the promise of improved performance and increased fault tolerance for large-scale problems. A robot team can accomplish a given task more quickly than a single agent by executing them concurrently. A team can also make effective use of specialists designed for a single purpose rather than requiring that a single robot be a generalist. Multi-robot coordination, however, is a complex problem. An empirical study is described in the present paper that sought general guidelines for task allocation strategies. Different task allocation strategies are identified, and demonstrated in the multi-robot environment. A simulation study of the methodology is carried out in a simulated grid world. The results show that there is no single strategy that produces best performance in all cases, and that the best task allocation strategy changes as a function of the noise in the system. This result is significant, and shows the need for further investigation of task allocation strategies.

KEYWORDS

Multi-Robot, Task Allocation, Strategies, Algorithms

1. INTRODUCTION

There is no general theory of task allocation in uncertain multi-robot domains. In this paper, an attempt is made to empirically derive some guidelines for selecting task allocation strategies for multi-robot systems. The explored strategies are individualistic in that they do not involve explicit cooperation and negotiation among the robots. However, they are a part of a large class approaches that produce coherent and efficient cooperative behavior.

Given the empirical nature of this work and the scope of the problem addressed, these guidelines are necessarily incomplete, though they provide useful insight. The demonstration that the choice of task allocation strategy is far from trivial and also empirically show that no optimal task allocation strategy exists for all domains, and that it can be very difficult to identify the optimal task allocation strategy even for a particular task. These results are derived through the use of a framework developed for understanding the task allocation problem, which illustrates a common approach to decomposing the problem. The approach presented in this paper can be advantageously used in real-world problems.

2. DYNAMIC TASK ASSIGNMENT

In the context of multi-robot coordination, dynamic task allocation can be viewed as the selection of appropriate actions [1] for each robot at each point in time so as to achieve the completion of the global task by the team as a whole. From a global perspective, in multi-robot coordination, action selection is based on the mapping from the combined robot state space to the combined robot action space. For homogeneous robots, it is the mapping

$$S^{|R|} \rightarrow A^{|R|}$$

where S is the state space of a robot, $|R|$ is the number of robots, and A is the set of actions

available to a robot [2].In practice, even with a small number of robots, this is an extremely high-dimensional mapping, a key motivation for decomposing and distributing control.

Based on the approach introduced in [3], the task allocation problem is decomposed into the following three steps:

1. each robot bids on a task based on its perceived fitness to perform the task;
2. an auctioning mechanism decides which robot gets the task;
3. the winning robot's controller performs one or more actions to execute the task.

The above decomposition is to construct a general formulation for the multi-robot coordination problem. In this formulation, a bidding function determines each robot's ability to perform a task based on that robot's state. Next, the task allocation mechanism determines which robot should perform a particular task based on the bids. Finally, the robot controllers determine appropriate actions for each robot, based on the robot's current task engagement. This partitioning, illustrated in Fig. 1, serves two purposes: it reduces the dimensionality of the coordination problem, and it reduces the amount of inter-robot communication required. We now have the mapping

$$B^{|R||T|} \rightarrow T^{|R|}$$

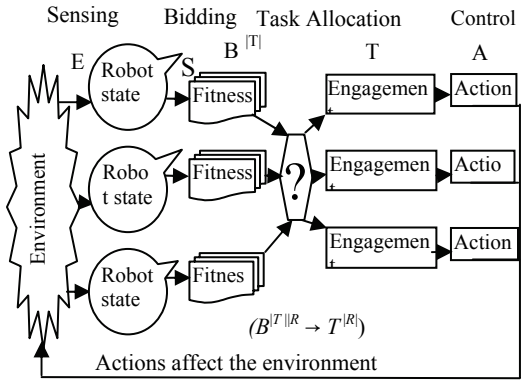


Figure 1 Reducing the Dimensionality of Multi-Robot Coordination

Instead of mapping namely from all robots' bids B for all tasks T to a task assignment for each robot, this overall mapping is called the Task Allocation Strategy for the system as a whole. The overall mapping is treated here as a global, centralized process (as depicted in Fig. 1), but distributed auctioning mechanisms [3,4], blackboard algorithms [5] , and cross-inhibition of behaviors [6] are some validated methods for distributing the task allocation function. In this methodology, the focus is on what the task allocation function should be, rather than on how it should be distributed. The above framework is a general way that dynamic task allocation for multi-robot systems can be formulated.

2.1 The Auction Algorithm

The auction algorithm is an intuitive method for solving the classical assignment problems. It outperforms substantially its main competitors for important types of problems, both in theory and practice, and is also naturally well suited for parallel computation. In the process, the user submits jobs to the auctioneer to start the process. An auctioneer is responsible for submitting and monitoring jobs on the user's behalf. The auctioneer creates an auction and sets additional parameters of the auction such as job length, the quantity of auction rounds, the reserve price and the policy to be used. The auctioneer informs the robots (Robot-1, Robot-2 and Robot-3) that an auction is about to start. Then, the auctioneer creates a call for proposals, sets its initial price, and broadcasts calls to all the robots (Robot-1, Robot-2 and Robot-3). Robots formulate bids for selling a service to the user to execute the job. The robots evaluate the proposal; they decide not to bid because the price offered is below what they are willing to charge for the service. This makes the auctioneer to increase the price and send a new call for proposal with this increase in the price. Meanwhile, the auctioneer keeps updating the information about the auction. In the second round, Robots are decided to bid.

The auctioneer clears the auction according to the policy specified beforehand. Once the auction clears, it informs the outcome to the user and the robots. The flowchart for the process is presented in Figure 2.

The algorithm described here can be utilized in task allocation in multi-robot applications, and is particularly suitable for parallel computation. This approach attempts to find the best assignment

between tasks and robots, while maximizing the total benefit. It iterates between robots and in each

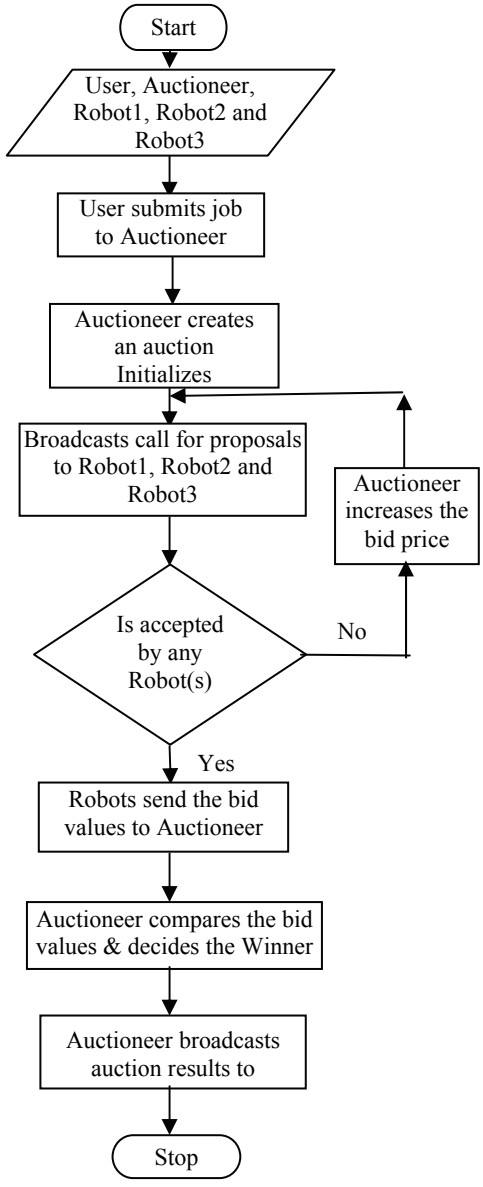


Figure 2 Flowchart of the Auction for Task Allocation

iterations tries to assign a task to a robot who offers the most. In consecutive iterations, other robots may bid for other tasks and if more than one bids for the same task, it will increase the cost of task until finally just one task-robot pair match takes place, i.e., iterative improvement. The iteration terminates when all robots are pleased with their match, otherwise an unhappy robot will bid higher for another task and this process will continue. Although auction algorithm may have some similarities to the free market approach, there is a little difference. One difference is that in the free market approach, agents can cooperate in order to gain a maximum profit for all of them, however in the auction algorithm every robot is considered rival. Another dissimilarity is that the auction algorithm uses an exclusive mathematical model for all the applications, while the free market approach does not. In addition, the free market technique is based on the collection of heterogeneous agents, while in the auction algorithm the robot set is homogeneous.

2.2. Task Allocation Strategies

The dynamic task allocation problem, i.e., the mapping from bids to tasks, can be performed in numerous ways. The focus is limited here to Markovian systems, where the task allocation mapping for a given robot is based on the mapping between that robot's current task assignments and every other robot's current bid on each task, to the given robot's new task assignment, as shown in Fig. 3. Given each robot's bid on each task and each robot's current task engagement, each robot's new task assignment need to be determined. The effects of two key aspects of distributed control, commitment and coordination, on performance are explored.

Given the large space of possibilities, only the extreme cases of each: no commitment and full commitment, and no coordination and full coordination are considered. The combination of these extremes results in four task allocation strategies as shown in Figure 4.

Along the commitment axis, a fully committed strategy meant a robot would complete its assigned task before considering any new engagements, while a fully opportunistic strategy allowed a robot to drop an ongoing engagement at any time in favor of a new one.

Along the coordination axis, the uncoordinated (individualistic) strategy meant each robot performed based on its local information, while a coordinated strategy simply implemented mutual exclusion, so only one robot could be assigned to a

task, and no redundancies were allowed. It is noted that this notion of coordination is simple, and not intended to represent explicit cooperation and coordination strategies instantly closes (i.e., the fixed time-cost was 0). Three new tasks appear every twelve time-steps at random positions on the grid. The tasks are structured so that one robot is sufficient for completion of an individual task assignment. Thus, mutual exclusion is the simplest yet effective form of coordination.

Current engagement	Bids	A	B	C	D	New engagement
A	R1	6	4	2	5	?
--	R2	4	1	0	3	?
C	R3	7	2	3	2	?

Figure 3 An Example Task Allocation Scenario

Commitment ⬇	Coordination➡	
	Individual	Mutually Exclusive
Commitment	Strategy.1	Strategy.2
Opportunity	Strategy.3	Strategy.4

Figure 4 the Four Task Allocation Strategies

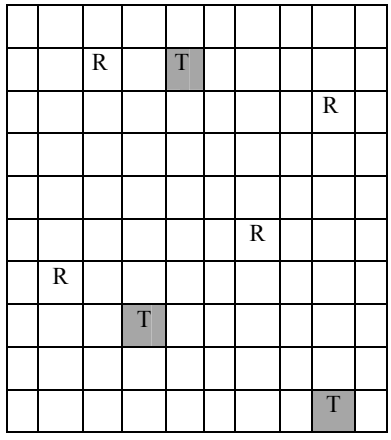


Figure 5 An Example 10 X 10 Grid World with Four Robots and Three Tasks

As an example, the fully committed mutually exclusive strategy is as follows:

1. If a robot is currently engaged in a task, and its bid on that task is greater than zero, remove the row and column of the bid from the table, and set the robot's new assignment to its current one.

2. Find the highest bid in the remaining table. Assign the corresponding robot to the corresponding task. Remove the row and column of the bid from the table.

3. Repeat from step 2 until there are no more bids. In case of individualistic (uncoordinated) strategies, the same algorithm is run on a separate table for each robot. In the opportunistic (uncommitted) case, step 1 above is skipped.

3. GRID WORLD EXPERIMENTAL FRAMEWORK

A simplified version of the above described multi-robot task in a grid world is illustrated in Fig. 5.. As the base case of the grid world implementation, a 10×10 grid inhabited by 10 robots is considered. Robots bid on tasks depending on their capability(expressed by a number) to those tasks. The bid was set to 20 − d, where d is the Manhattan distance to the task. In each time-step, any robot assigned to a particular task selects that task. When a robot selects a task, that task .

Strategy:	I,O	I,C	M,O	M,C
Results:	980	1045	435	722

Figure 6 Results from Base Case Grid World

In order to explore the parameter space of the task, we focused on *commitment* and coordination. In the context of emergency handling, commitment means that robots stay focused on a single task, until the task is over. The opposite, *opportunism,* means that robots can switch tasks, if for example another task is found with greater intensity or priority. In the experiments, coordination is linked to communication, namely the ability of robots to communicate about who should service which tasks, as opposed to *individualism,* where robots have no awareness of each other. Communication is used to prevent multiple robots from trying to accomplish the same task; robots inhibit others from engaging in the same task. The goal is to reduce interference among robots, and to prevent loss of coverage in some areas because all the robots rush to perform task in another area. Deciding the level of commitment and collaboration are key aspects of the multi-robot task allocation problem. Four experiments were

designed resulting from the combinations in varying the two parameters, coordination and commitment. The results of the grid world simulation are presented in Fig.6.On one axis we test commitment versus opportunism, and on the other we test individualism versus mutual exclusion.

4. THE BLACKBOARD ALGORITHM

To ensure reasonable scalability and robustness, communication among the robots is done through a "blackboard". To simulate experiments with inter-robot communication, each robot sends its relevant state information to the blackboard, and the blackboard information is read by all the robots. In the case of no communication, the blackboard just contains information from one robot (itself). The information on the blackboard is the current engagement of each robot. Intuitively, if all robots have the same blackboard information available and execute the same algorithm, they should all come to the same conclusion as to which robot should pursue which task.

Table 1 Quantitative Results

Results	Individ.		Mut. Exclusion	
Commitment	2063	1	2325	2
	2016	2	1919	1
	1786	2	2008	1
Opportunism	1087	0	2061	2
	928	0	1406	1
	1917	0	1078	0
			1322	0

To facilitate validation of the experiments, all parameters are held constant, except the way the information on the blackboard is handled. The algorithm for deciding which robot should do what is as follows:

Step 1: All robots engaged in a task cannot have their engagement set to “none”

Step 2: In case of commitment, all entries in the blackboard for robots already pursuing a task is set top zero, along with all entries for task already being pursued. In case of opportunism, this step is skipped.

Step 3: The highest non-zero score in the table is found, and the robot corresponding to this entry is assigned to the task corresponding to this entry.

Then all entries of the robot and the tasks are set to zero. Step 3 is repeated with the new table, until no new assignments are made. Table 1 presents the quantitative where the larger numbers are total sum of on-line for tasks in each trial. The smaller numbers are tasks left at the end of the trial. The algorithm has the effect that in the case of commitment robots keep themselves engaged in performing a task until it is complete, while in the opportunism, robots keep switching engagements.

5. DISCUSSION

The grid world results are interesting if they actually represent real world system behavior. The fact that the best performing task allocation strategy changes as we vary noise parameters in the grid world implies that it can be very difficult to decide *apriori* which task allocation strategy should be used in a given task for any real world implementation. The experiments clearly show that the opportunistic strategy worked significantly better than the commitment-based strategy. This might be because the time to reach a task was significantly larger than the time to complete a task, once a robot was there. This choice of parameters favors opportunism over commitment since the former effectively uses the presence of robots near emergencies by harnessing them immediately. In other regions of the parameter space of the emergency handling task (e.g., where the ratio of time-to-reach-task to time-to-complete-task is small) opportunism might not be as effective. The present study excluded the case where several robots would be required to do a task in a cooperative fashion, a regime in which performance might improve with commitment.

The four task allocation strategies we examined are *extreme*, in that they take into consideration only the complete presence or absence of commitment and coordination in the given context. Arguably, the best strategy for any particular task would most likely be a carefully balanced compromise. However, as stated previously, the goal of this work was not to attempt to find the best strategy (which is necessarily task- and parameter-specific), but rather to gain some insight into task allocation in general. The four strategies

we explored provide a reasonable span of strategy space and provide leading insights for further study. In practice, the robot capability ratings can be obtained from the databases. Therefore, one can automatically select appropriate candidate for a given task by using the proposed matching procedure and databases.

6. CONCLUSION

The paper describes an empirical study that sought general guidelines for task allocation strategies in systems of multiple cooperating robots. Four distinct task allocation strategies are identified that aim at studying tradeoffs between commitment and coordination. The data from the simulations show that there is no single strategy that produces best performance in all cases, and that the best task allocation strategy changes as a function of the noise in the system. This result is significant, and shows the need for further investigation of task allocation strategies. The described work is a small step toward the larger goal of principled analysis and synthesis of multi-robot coordination strategies for complex and uncertain domains, such as space exploration. The entire exercise has relevance to real world distributed robotics terrestrial and space applications.

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OPTIMAL CONTROLLER DESIGN FOR TWO ARM MANIPULATORS USING QUANTITATIVE FEEDBACK THEORY METHOD

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ABSTRACT

In this paper, a practical method to design a robust controller for a two-arm manipulator using Quantitative Feedback Theory (QFT) is proposed. As the two arm manipulators have, multivariable nonlinear transfer function, implementation of QFT technique requires first to convert its nonlinear plant into family of linear and uncertain plant sets, then an optimal robust controller will be designed for each set. In order to illustrate the utility of our algorithm we present the application of it to a two degree of freedom robot arm manipulator. An optimal robust controller is designed for tracking problem. At the end nonlinear simulation for tracking problem in an arbitrary path has been carried out which indicates successful design of controllers and prefilters.

KEYWORDS

Two Arm Manipulators, QFT, Loop Shaping, Dynamic Equations

1. INTRODUCTION

The purpose of a robot is to control the movement of its gripper to perform various industrial jobs such as assembly, material handling, painting, and welding [1]. Robot manipulators have complex nonlinear dynamics that might make accurate and robust control difficult. Fortunately, robots are in the class of Lagrangian dynamical systems, so that they have several extremely nice physical properties that make their control straight forward [2]. There are several methods for controlling of a robot such as: classical joint control, digital control, adaptive control, robust control, learning control, force control, and teleoperation. In this paper we consider the two arm manipulators as a two degree of freedom nonlinear multiple-input multiple-output (MIMO) system and as a controlling technique Quantitative Feedback Theory (QFT) will be used.

There are many practical systems that have high uncertainty in open-loop transfer functions which makes it very difficult to have suitable stability margins and good performance in command following problems for the closed-loop system. Therefore a single fixed controller in such systems is found among "robust control" family.

Quantitative Feedback Theory (QFT) is a robust feedback control system design technique introduced by Horowitz (1963, 1979), which

allows direct design to closed-loop robust performance and stability specifications.

Consider the feedback system shown in diagram Fig.1. This system has two-degrees of freedom structure. In this diagram p(s) is uncertain plant belongs to a set $p(s) \in \{p(s,\alpha); \alpha \in p\}$ where α is the vector of uncertain parameters for uncertainty structured of p(s), G(s) is the fixed structure feedback controller and F(s) is the prefilter. [3], [4].

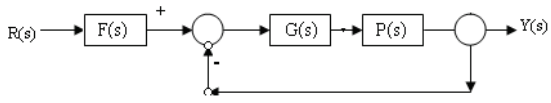


Figure 1 Structure of a Two Degrees of Freedom System

2. DYNAMIC EQUATIONS OF THE ROBOTIC MANIPULATOR

Fig.2 depicts a two degree of freedom robot, where m_1, m_2 are the masses of links 1, 2 and l_1 , l_2 are the length of the links 1, 2 respectively. The dynamic equation of the robotic manipulator is [5].

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \tag{1}$$

$$M(q) = \begin{bmatrix} (\frac{1}{3}m_1 + m_2)l_1^2 + \frac{1}{3}m_2 l_2^2 + m_2 l_1 l_2 \cos q_2 & \frac{1}{3}m_2 l_2^2 + \frac{1}{2}m_2 l_1 l_2 \cos q_2 \\ \frac{1}{3}m_2 l_2^2 + \frac{1}{2}m_2 l_1 l_2 \cos q_2 & \frac{1}{3}m_2 l_2^2 \end{bmatrix}$$

$C(q,\dot{q})$ is a 2×2 matrix of coriolis and centrifugal forces that can be described as:

$$C(q,\dot{q}) = \begin{bmatrix} -\frac{1}{2}m_2 l_1 l_2 (2\dot{q}_2) & -\frac{1}{2}m_2 l_1 l_2 \dot{q}_2 \sin q_2 \\ \frac{1}{2}m_2 l_1 l_2 \dot{q}_1 \sin q_2 & 0 \end{bmatrix}$$

And $G(q)$ is a 2×1 gravity vector that can be represented as:

$$G(q) = \begin{bmatrix} (\frac{1}{2}m_1 + m_2) g l_1 \cos q_1 + \frac{1}{2}m_2 g l_2 \cos(q_1 + q_2) \\ \frac{1}{2}m_2 g l_2 \cos(q_1 + q_2) \end{bmatrix}$$

Where g represents gravity acceleration constant.

The following numerical values are chosen for the robot manipulator

(m1=2kg, m2=3kg, L1=0.4m and L2=0.6m)

So, dynamic equations of the robot can be derived as follows:

$$\begin{cases} \tau_1 = \left(0.9467 + 0.72\cos(q_2)\right)\ddot{q}_1 + \\ \left(0.36 + 0.36\cos(q_2)\right)\ddot{q}_2 - 0.72\dot{q}_1\dot{q}_2 - \\ 0.36\dot{q}_2^{\,2}\sin(q_2) + 15.68\cos(q_1) + \\ 8.82cos(q_1 + q_2) \\ \tau_2 = \left(0.36 + 0.36\cos(q_2)\right)\ddot{q}_1 + 0.36\ddot{q}_2 + \\ 0.36\dot{q}_1^{\,2}\sin(q_2) + 8.82cos(q_1 + q_2) \end{cases} \tag{2}$$

Block diagram representation of the above equations which simulates nonlinear multivariable dynamics of robot in Matlab is show in Fig 2.

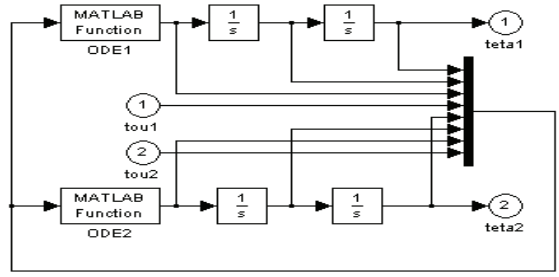


Figure 2 Simulation of Robot Dynamic in Matlab

3. DESIGN OF QFT CONTROLLER FOR NONLINEAR SYSTEMS

3.1 Linearization

In QFT method, the nonlinear plant is converted to family of linear and uncertain processes. In this paper a simple new method is implemented to apply the above conversion.

Angular velocity, acceleration and required torque for different trajectories can be calculated, simulating the nonlinear model [7], based on these data equivalent linear plant will be derived for each arm as below:

In result linearized transfer function for each arm can be obtained as follows:

$$P_i = \frac{1}{s(J_{eff}.s + C_{eff})} \qquad \text{i=1, 2} \qquad (3)$$

3.2 Template Generation

Figs.3, 4 show plant uncertainty in Nichols chart for each arm. The linear uncertain plant transfer functions of manipulator can be modeled as below:

1) Arm one $P_1 = \frac{1}{s(J_{eff}.s + C_{eff})}$ (4)

J_{eff} = [5.3838, 7.3716]

C_{eff} = [27.9061 55.7397]

2) Arm two $P_2 = \frac{1}{s(J_{eff}.s + C_{eff})}$ (5)

J_{eff} = [3.1258 4.1913]

C_{eff} = [-.3417 17.4859]

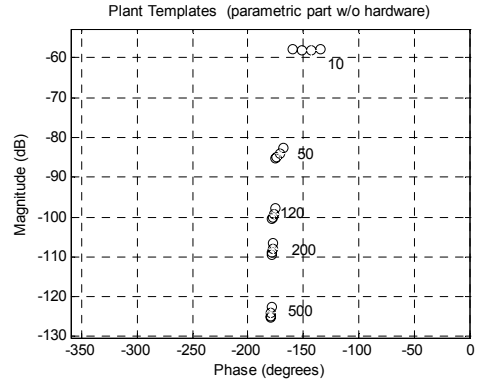


Figure 3 Uncertainty Templates for Arm 1

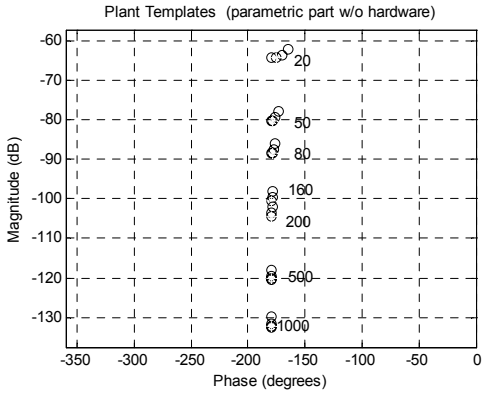


Figure 4 Uncertainty Templates for Arm 2

3.3 Tracking Problem

The overshoot and the settling time specifications (M_p =5%) and (T_s =0.05 s) respectively are given in the form of upper and lower bounds in frequency domain, usually based on simple second-order models to represent the status of damped condition .Fig 5, 6. [5]

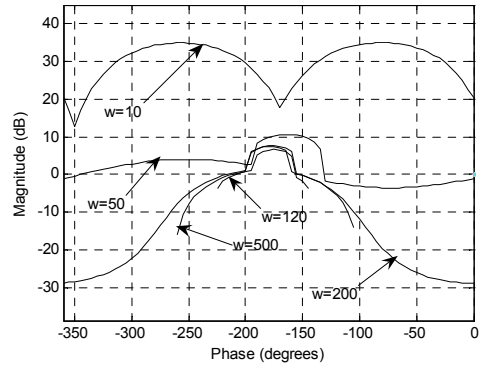


Figure 5 Robust Tracking Bounds for Arm 1

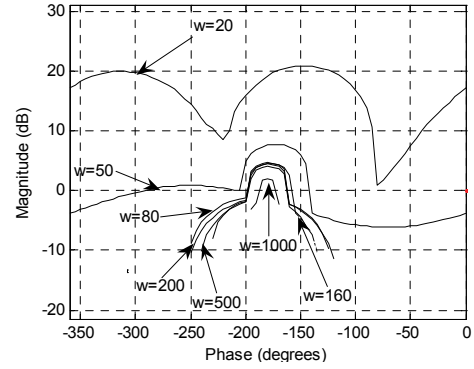


Figure 6 Robust Tracking Bounds for Arm 2

3.4 Robust Margins

The following two conditions to achieve robust stability are:

First, stability of the nominal system which means: the Nichols chart envelope should not intersect the critical point *q* (-180°, 0 *dB*). [4]

Second, magnitude constraint condition which means: placing a magnitude constraint on the complementary sensitivity function.

$$\left|\frac{1}{1+1}(j\omega)\right| < 1.05 \quad \text{for each arm. Fig. 7, 8} \qquad (6)$$

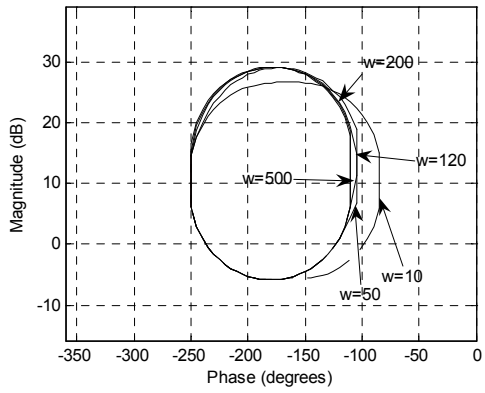


Figure 7 Robust Margins Bounds for Arm 1

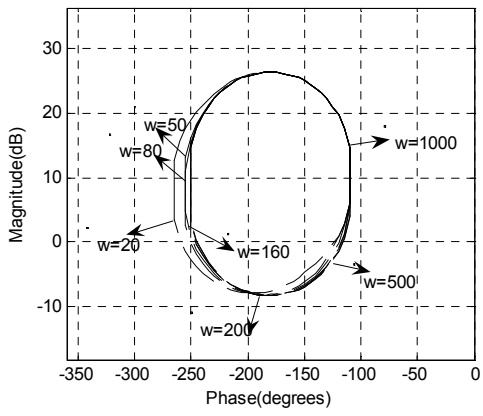


Figure 8 Robust Margins Bounds for Arm 2

3.5 Loop and Pre-Filter Shaping

By using the elements of the QFT toolbox we design the controller so that the open loop transfer function exactly lies on its robust performance bounds and does not penetrate the U-contour at all frequency values (ω_i).Fig. 9, 10. The design of pre-filter guarantees the satisfaction of tracking specification. In Figs. 11, 12 pre-filter shaping of open loop transfer function for each arm is shown. So the optimal controller and pre-filter are designed and given as below:

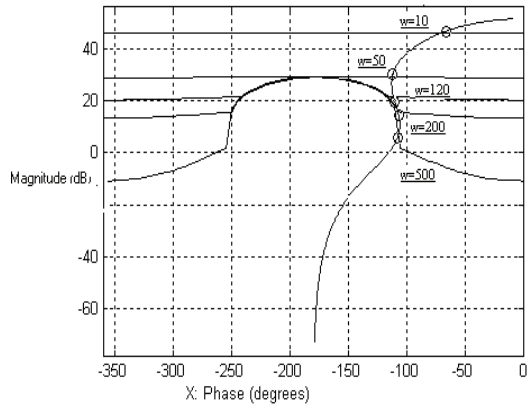


Figure 9 Loop-Shaping in Nichols Chart for Arm 1

$$G(s) = 238.33\frac{s(s+77.58)}{\left(\frac{s}{26.76}+1\right)\left(\frac{s}{2213}+1\right)} \qquad (7)$$

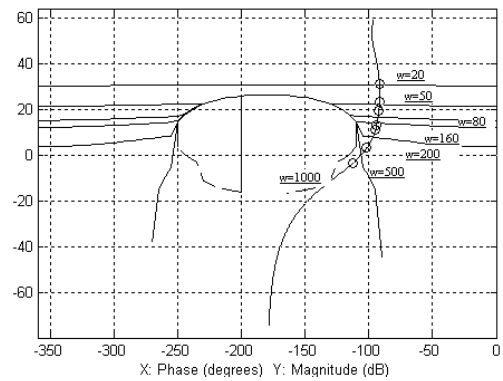


Figure 10 Loop-Shaping in Nichols Chart for Arm 2

$$G(s) = 3033.3\frac{(s+2.012)}{\left(\frac{s}{2444}+1\right)} \qquad (8)$$

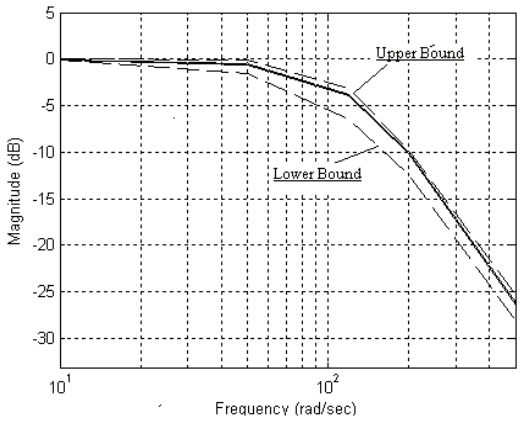


Figure 11 Pre-Filter Shaping in Nichols Chart for Arm 1

$$F(s) = \frac{138.1^2\left(\frac{s}{204.3}+1\right)}{\left(\frac{s}{122.1}+1\right)\left(s^2+207.15\,s+138.1^2\right)} \qquad (9)$$

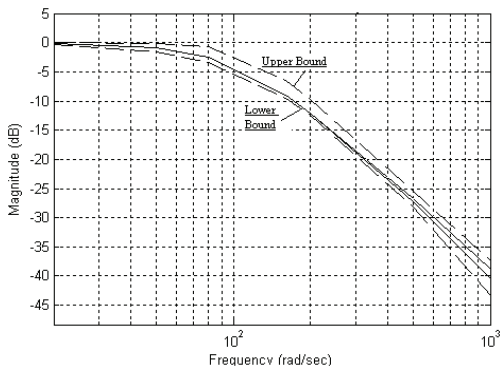


Figure 12 Pre-Filter Shaping in Nichols Chart for Arm 2

$$F(s) = \frac{107.5^2\left(\frac{s}{1542}+1\right)}{\left(s^2+181.1\,s+107.5^2\right)} \qquad (10)$$

3.6 Analysis of Design

The time domain closed loop response of each arm including controller and pre-filter is shown in Figure 13 and 14 respectively which indicates the design is accurate.

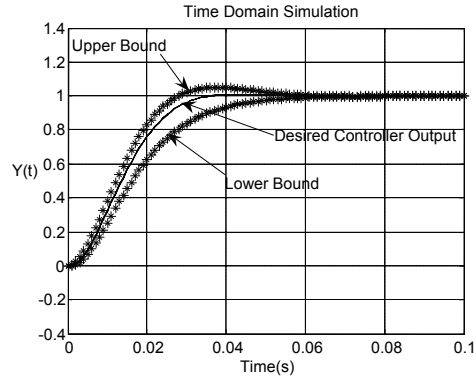


Figure 13 Step Response and Control Effort of System with G(S) and F(S) for Arm 1

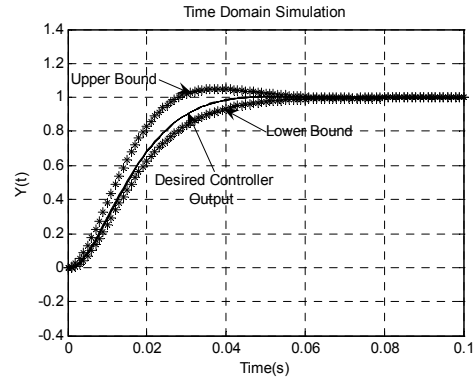


Figure 14 Step Response and Control Effort of System with G(S) and F(S) for Arm 2

3.7 Nonlinear Analysis of Robot with Controller

The result of tracking problem for an elliptical path is shown in Fig .15, while Fig.16 depicts the End Effecter error in Cartesian coordinate system (for x & y directions)

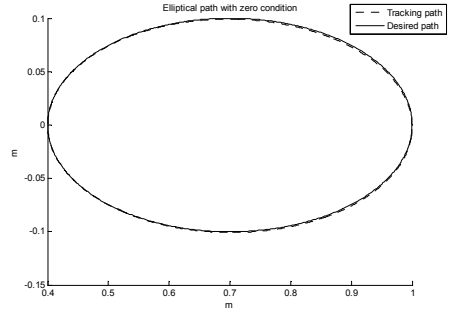


Figure 15 Tracking Problem for Elliptical Path

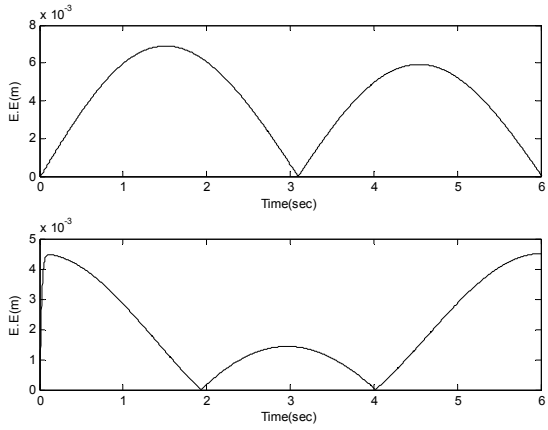


Figure 16 End Effecter Error in Cartesian Coordinate System (for X & Y Direction)

4 CONCLUSION

This paper implements a new algorithm for designing optimal controller for robot arm manipulators applying QFT technique. Our research indicates that increase of accuracy in tracking problem, has direct relationship with following matters:

1) Reduction of settling time in tracking bounds for associated linear system
2) Improvement of associated linear uncertain system modeling.
3) Successful implementation of robust controller design for a two arm manipulator.

We should notice that tracking accuracy by using tighter robust performance bounds could be increased which in turn leads to an increase in the controller gain, therefore based on the design limitation suitable solutions will be obtained.

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24th International Symposium on Automation & Robotics in Construction (ISARC 2007)
Construction Automation Group, I.I.T. Madras

CONCRETE PAVING PRODUCTIVITY IMPROVEMENT USING A MULTI-TASK AUTONOMOUS ROBOT

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ABSTRACT

To improve productivity in conventional concrete construction, autonomous robots that perform specific tasks are being developed. Single-task robots are capable of enhancing specific functions, though their impact on the overall productivity remains unclear. A robot that incorporates each task-specific piece of machinery used in the concrete paving process into one fully autonomous unit is evaluated. Assessing potential productivity from the use of a fully automated process is a required step for developing a full scale-system. With the purpose of identifying productivity benefits in an automated concrete paving operation, two concrete paving processes will be compared using simulation tools. One process is the conventional operation using intensive labour, slip form paving machine and auxiliary equipment. The other process is the automated operation using a fully autonomous robot. Applications of this assessment methodology based in simulation will allow for the determination of productivity indicators of automated operations in hazardous environments, using the respective results to complement prototypical tests.

KEYWORDS

Pavement, Robotics, Computer-Based Simulation, Productivity

1. INTRODUCTION

Robotics has been subject of study in civil engineering for the past twenty years, thereby generating great interest in the construction community [1, 2]. Theoretical benefits based on prototypical performances have the potential to provide competitive advantages for construction firms, given the productivity, safety and quality improvements offered by robots when performing both simple and complex construction tasks.

Concrete pavement construction is suited for robotics in that the complete construction process is made up of many single tasks that can be automated and integrated into one single machine. A fully autonomous robot will have the ability to consistently produce high-quality products and to precisely perform tasks. It is envisioned that with the aid of an autonomous robot, construction projects will be able to be completed better and faster, which will lead to greater productivity and reduce costs.

1.1 Concrete Paving Operations

The actual concrete paving operation is a combined process of a large number of specially-designed machines, each with a specific function in the construction process. Once paving operations have begun, the various steps in the construction process are arranged in the form of a continuing series of separate operations that are planned and coordinated so that the construction proceeds with minimum loss of time and effort. Each of the separate steps must be done carefully and precisely so that the completed pavement will meet the applicable standards for structural strength and smoothness. Other important aspects in the paving process include the control of the paving equipment trajectory and the control of the pavement surface profile, or screeding. Currently, most of the methods used to control equipment trajectory are based on conventional surveying techniques, such as hubs, grade stakes and string-lines. These types of controls limit productivity, because their installation is slow and are subject to human errors. In addition, manual-type trajectory controls require skilled operators to accurately steer the equipment, using rudimentary techniques. There is ongoing research in the evaluation of stringless paving using a combination of global positioning and laser technologies [3]. However, results are indicating that GPS control is a feasible approach to controlling a concrete paver, but further enhancements are needed in the physical features of the slip-form paver hydraulic system controls and in the computer program for controlling elevation. In some state-of-the-art paving operations, laser levelling systems have been introduced to improve productivity and accuracy of the paving process. These systems consist of a ground-based laser source that emits a linear beam or light pulses, with target receivers mounted on the paver. Although the use of laser technology is widespread in the excavation industry for grade control, only a few of the commercially available pavers have the capability for minimal laser control. Furthermore, no current commercially-available paver has the ability for semi-autonomous operation of the screed and trajectory using laser-based or any other technology. Furthermore, control of the screeding operation is also based on conventional surveying techniques.

Conventional concrete paving operations require a great deal of resources and are labour intensive, even with state-of-the-art pavement equipment. There are many competitive advantages to integrating robotic technology with concrete pavement construction. Although the concept of using a robot for asphalt paving has been shown to be valid with the development and demonstration of the Road Robot [4], no attempts have been made to expand that research to concrete paving. Integrating the paving and post-paving operations into one fully autonomous robot, which also included a laser-based guidance and positioning system, sensors to monitor materials and machine operation, and providing remote data reporting capabilities would significantly improve efficiency and productivity in concrete paving. By increasing productivity while decreasing the personnel and equipment required performing the work, a concrete paving robot would also reduce the cost of pavement construction.

1.2 Robopaver: Fully Autonomous Robot for Concrete Paving

A prototype of a fully autonomous robot for concrete paving, dubbed Robopaver, is presently being developed [5, 6]. The prototype is a 1:20 scaled model of the intended field version. The purpose of the prototype is to serve as a proof-of-concept concrete pavement construction robot. It is anticipated that the full-scale version of the Robopaver will occupy about the same volume as a typical commercially-available slip form paver, but will combine all the operations of a conventional paving train into one robot.

The Robopaver proof-of-concept hardware prototype will incorporate each task-specific piece

of machinery used in the concrete paving process into one fully autonomous unit. The Robopaver prototype will be a battery-operated robot that will consist of several different operations: placing pre-fabricated steel reinforcement bar cages; placing and distributing concrete; vibrating; screeding; final finishing; and curing. Figure 1 presents the conceptual design of the Robopaver prototype.

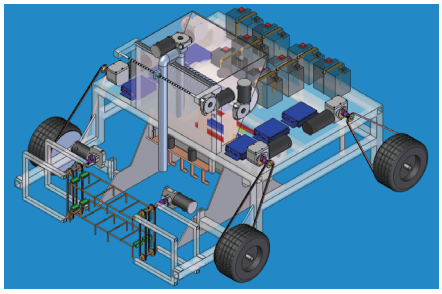


Figure 1 Conceptual Design of Robopaver [6]

The first operation that the autonomous concrete paving robot will perform is the placement of pre-fabricated steel reinforcement cages. In conventional concrete paving operations, dowel bar baskets are manually assembled and placed along the sub grade prior to the paving operation. Automating placement of these baskets will improve efficiency and decrease costs by decreasing the number of required pre-paving activities. The pre-fabricated steel reinforcement cage and the placement system included in the Robopaver simulates placement of the dowel bars and tie bars. The Robopaver will have a racking system that will store and dispense the pre-fabricated reinforcement cages. The reinforcement racking and placing system is made up of two conveyor belts that will move uniformly to place the prefabricated reinforcement cages. Depending on the desired width to be paved, the two-conveyor racking systems will be able to accommodate different distances by moving closer or farther apart. A robotic arm or fork lift mechanism may be added for greater control over the placement of the reinforcement bars. Placement of the cages will be controlled by onboard sensors that compare the position of the robot with the specified location of the reinforcement. Once at the prescribed location, the side conveyors will advance to drop down the reinforcement.

A holding tank with a mixer and dispersing mechanism will be used to place concrete, while the mixer will be a motor-driven auger screw. The dispersing mechanism will consist of a pump and a pipe mounted on a double threaded screw. The vibrating, screeding, and final finishing of the placed concrete will be performed under the main body of the robot. In the full-scale design, the vibrating would be done hydraulically. For the proof-of-concept hardware prototype, the possibilities to perform this task range from using a vibrating motor to developing a reciprocating press. Vibrator mechanisms for both Robopaver and a conventional slip-form paver are depicted in Figure 2.

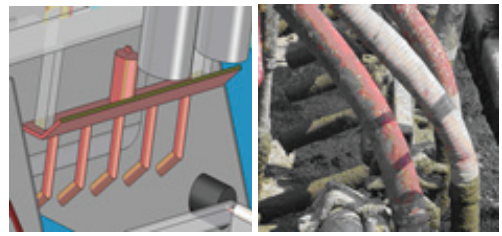


Figure 2 Vibrator Mechanisms of Robopaver and Conventional Slip-form Paver

The concrete is drawn up through the pipe by an auger driven by the motor mounted on the top of the pipe. In order to disperse the concrete evenly, the pipe is attached to a double threaded lead screw that will cause the pipe to oscillate back and forth in the section being paved.

Different batches of concrete will vary in content and viscosity. Testing should be done on the draw current of the mixing motor for an optimal batch of concrete. Laser profiling sensors can also be placed in front of the paver to ensure that there is enough concrete on the ground to continue moving the paver forward. To allow for the form to move up and down, two sets of track bearings were added, plus two linear electric actuators that can supply 700 lbs of force apiece. Because the form will be moving, the final screed must move along with it. In order to do this, the prototype's screed system is welded onto the form. The screeding subsystem will be composed of oscillating steel plates that will produce a layered finish. This approach is similar to what is done in standard practice. Another operation performed underneath

the main body will be the final finishing. This subsystem will incorporate laser levelling technology controlling a steel roller that will slide on a track.

2. PRODUCTIVITY ANALYSIS

In order to identify productivity benefits and safety aspects in the paving operation, two processes were compared using simulation tools. One process is the conventional paving operation using intensive labour, slip form paving machine and auxiliary equipment. Data for this operation was available through a pool of 125 paving projects in the state of Ohio, United States, during 2003 and 2004. The other process is the automated paving operation using a fully autonomous robot. Data for the assembly of the workflow was based on three sets of sources: First, process layout derived from prototypical performance estimates; second, addition or elimination of tasks that are required or no longer needed; and third, reduction of variability of task duration.

2.1 Conventional Paving Process

STROBOSCOPE [7] is a simulation system designed specifically for construction, and uses a network of elements to represent the essentials of a model. The models were represented using activity cycle diagrams (ACD) with networks of circles and squares that represent idle resources, activities, and their precedence. Values from standard manuals for heavy construction and pilot data populated the assembly of linear workflows that yielded daily operational values using discrete event simulators specialized in construction operations. For instance, a 25 cm thick concrete pavement operation, including joints, finishing and curing has a theoretical daily output of 1,756 square meters (m^2) and a cost of \$44.85 per m^2 [8]. Based on a survey of repetitive concrete paving on 125 jobs in the state of Ohio, the average unit cost to a contractor is \$29.30 per m^2. The ACD for the existing concrete paving workflow is shown in Figure 3.

The crew involved in this operation consists of 1 labour foreman, 6 labourers, 1 equipment operator, 1 rodman and 1 cement finisher. This crew yields a national average, according to standard data, of 0.050 labour hours per m^2 and 0.142 labour hours per m^2 according to the pilot study from Ohio data

The testing phase of the Robopaver prototype comprised measurements of productivity that intend to be comparable to theoretical values. The Robopaver is expected to be more productive than typical practices due to the reduction of task interferences and crew.

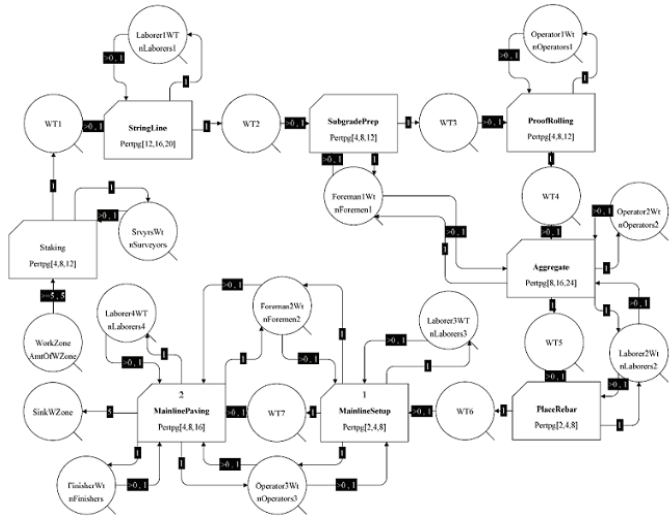


Figure 3 Existing Paving Process ACD

With the simulation results, it was intended to corroborate the level of magnitude of the values such as 1,756 m^2 per day indicated in standard manuals. Data for the conventional and proposed concrete pavement construction workflows were based on a standard 4,180 m^2 (5,000 square yards) project. Units for task duration are hours and were represented by probabilistic distributions, which originate from a pool of 2003 and 2004 project data for a typical paving contractor in the state of Ohio, United States. Durations of tasks were represented by PERTPG distributions, that rely upon assumptions of an optimistic, most likely and pessimistic activity duration.

2.2 Robopaver Process

The ACD for the autonomous concrete paving operation is shown in Figure 4. The only piece of equipment or labour involved in the automated operation consists of a logistics crew (one truck and one operator) that refills the hopper with concrete material, storage tanks with water and

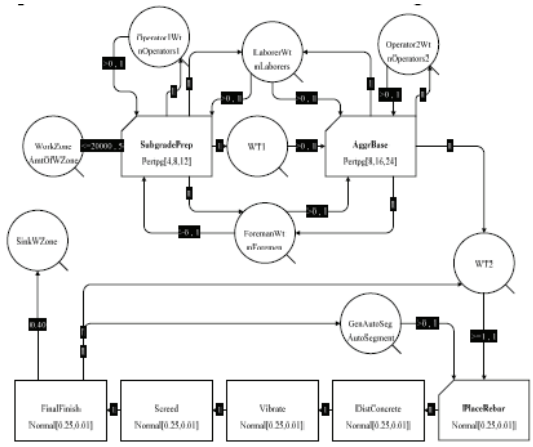


Figure 4 Robopaver Process ACD

other assemblies with rebar or curing compound as advised by the signals read in the control office. The robot prototype will provide insights and clues on the ultimate performance of the full scale robot, and its development and construction will prove or reject some of the findings of this paper, but simulation provided initial indicators and exposed opportunity areas for further research. Among others, the robot will have expectations in productivity improvement by achieving a reduction in surveying time with the use of GPS technologies, decrease in duration of particular tasks such as rebar placing, mainline setup, screeding and finishes due to the lack of crew interferences and set up times.

2.3 Simulation Results

Both processes were run for a simulated time of 500 hours. Results of the simulation are presented in Table 1.

Results from Table 1 suggest that the automated process is more productive than the conventional, for both the controlled run of 500 hours (gain of 20%) and the productivity at steady state (gain of 7.5%). Units in the sink queue at the end of the simulation exercise are also an indication of productivity improvement when adopting the automated process (gain of 21.3%). Another objective was to test the percent utilization of a critical resource (Foreman1) in both scenarios. Even though the automated operation does not call for the utilization of many resources, as it is indeed the case in the conventional situation, it is possible to determine the percent utilization of a single resource and compare between both scenarios. Results show that there is an increase in 56.4% in the utilization of the foremen when adopting the automated process, thus optimizing the use of this resource. In the conventional operation, however, two foremen are needed because if one is removed, then the overall productivity will decay, as it was proved when the software was run.

Table 1 Simulation Results

Process	Current	Robopaver	Gain(%)
Time (hr)	500	500	
Output (units)	125,000	151,600	21.3
Productivity (m^2/hr)	209	251	20.0
Productivity (m^2/day)	1,672	2,008	20.0
Steady State (m^2/hr)	248.8	267.5	7.5
Steady State (m^2/day)	1,990.5	2,140.0	7.5
Foreman Utilization (%)	42.7%	99.1%	56.4

Another benefit of simulation is the determination of the most adequate scenario for the deployment of the automated paving process. Furthermore, the robot has to meet the prototypical estimates shown in Figure 4 for the task durations in a working area of 334 m^2 (400 square yards); otherwise the productivity of the overall operation system will be compromised. By concentrating on this aspect of the operation performance, the design of the full scale robot can be adjusted to comply with these parameters.

3. CONCLUSIONS

The performance assessment of a fully autonomous robot that will be used for concrete pavement construction is presented, and its implications in productivity and safety. Concrete pavement construction is suited for robotics in that the complete construction process is made up of many single tasks that can be automated and integrated into one single machine.

Two equivalent paving processes, one conventional and one automated, were compared with the use of simulation tools, incorporating the resources needed for the completion of tasks and representing the durations with field data and prototypical estimates. Results show that the automated process is more productive, thus yielding productivity values up to 20% higher when simulated for 500 hours, or 7.5% higher after reaching steady state in the curve of productivity versus time. In comparison with theoretical values from a widely used standard manual, e.g., 1,756 m^2/day, the automated process reaches 2,140 m^2/day, representing a gain of about 22%. The automated process utilized considerably less labour than the conventional one, thus making the construction work zone less prone to accidents involving construction workers. The robot is designed to conduct the paving process without operators, labourers or foremen involved.

Finally, simulation allowed for the determination of the most adequate scenario for the deployment of the automated paving process, guiding robot designers to meet the most appropriate parameter estimates for task durations. Applications of this assessment methodology based in simulation will allow for the determination of productivity and safety indicators of automated operations in hazardous environments or construction in the space, using such results to complement prototypical tests.

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THE STUDY IN USING AN AUTONOMOUS ROBOT FOR PAVEMENT INSPECTION

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ABSTRACT

Traditionally pavement inspections are conducted using manually operated instruments, and hence are very labor-intensive. In this study, the authors propose the idea of using an autonomous robot to perform the pavement inspections, including for evenness and distress. Because inspection instruments are assumed to be mounted on the robot's platform, this robot is capable of inspecting pavement conditions while at the same time planning the upcoming motion path according to the inspection results. Working concurrently in this way significantly reduces the overall inspection time and amount of data to be stored. The authors propose four motion planning methods for robots: a transversal path planning method, a longitudinal path planning method, a random walk method, and an obstacle avoidance method. This paper presents the application of the motion planning methods to different pavement inspection tasks. It also illustrates the inspection process in a predefined inspection area, and in an inspection area that has random obstacles. The results of this research are suitable for use with a commercial robot to achieve the goal of robotic pavement inspections.

KEYWORDS

Autonomous Robot, Pavement Inspection, Pavement Evenness, Pavement Distress, Path Planning

1. INTRODUCTION

Among common infrastructure, roads are one of the most difficult to maintain. The road usually locates broadly in various weather and traffic conditions. They are often worn due to traffic passage, changeful temperatures and the random impacts of vehicles. Different deterioration rates and randomly occurring distresses increase the complexity of maintaining and managing the pavements on roads.

Since road users can easily perceive the pavement problems, most governments try to maintain the pavements as best they can. In most cases, road authorities periodically inspect pavements and keep the conditions above an acceptable serviceability (the quality of pavement for road users) and determine appropriate and timely maintenance and rehabilitation (M&R) activities. Appropriate M&R activities not only prolong pavement life but also save life-cycle costs; as well as provide comfortable and safer pavements for road users [1].

Successful M&R activities rely on effective pavement inspections with proper approaches and within budget. It also requires careful allocation of limited resources such as inspection instruments and operators. However, in current inspection processes, the inspection plans are developed subjectively by engineers prior to inspections. After planning is complete, the inspection tasks are conducted using manually operated instruments. These inspections usually include repetitive and tedious procedures, and often require a great amount of time for post-analysis.

In the study, the authors pioneered the idea of using an autonomous robot to perform the pavement inspections to reduce the overall resource cost. With self-controlled motion and automatic path planning, robots can reduce the variation and uncertainty of inspections; and, the reliability of inspections would be improved.

2. PAVEMENT INSPECTION

The serviceability provided by pavement is highly related to surface condition. In general, the surface conditions are monitored by periodically collecting the longitudinal evenness (roughness), transversal evenness (rutting), and distress information using of manifold commercial equipment [2].

2.1 Pavement Evenness

For flexible pavement, roughness and rutting are the variations of longitudinal and transversal profiles respectively. Both are important for comfortable driving or riding for road users. In the past decades, the instruments developed for roughness inspection were improved through automation. In general, the roughness instruments are grouped into four types: Profiler/Profilograph, Response-Type Road Roughness Measuring Systems (RTRRMSs), Inertia Profilometer/Lightweight Profilometer, and Walking Profiler [2].

2.2 Pavement Distress

A pavement distress survey is conducted to monitor the present pavement condition and determine the appropriate M&R activities. The common distress types include alligator cracking, longitudinal cracking, transverse cracking, block cracking, rutting, and patching. Toward the end of the 1970s, Darter and Shahin [3] developed the Pavement Condition Index (PCI); which, has been referred as ASTM D6433 [4] for roads and parking Lots and ASTM D5340 [5] for airfield pavement. Manual and automatic approaches are the two major ways, adopted all over the world, to conduct a pavement distress survey. The manual approach is conducted through visual observation. The severity and coverage of each distress on one pavement unit are identified and recorded using pen and paper or a personal digital assistant (PDA). The PCIs can be computed immediately using the PDA or manually during the post-processing. The automatic approach is to first capture pavement images, and then the severity and coverage of each distress are automatically identified through image processing algorithms. The PCIs and their accuracy are computed immediately or semi-automatically during the post-processing. However, present image processing merely focuses on linear cracking and potholes thus could not replace the manual approach. Significant developments have taken place as far as automating the distress measurement is concerned. There are lots of inertial profilers that automate the

complete distress date collection. More literatures can be referred as [6, 7].

Most evenness and distress inspections on broad pavements are conducted using a repetitive and time-consuming procedure that uses human-operated instruments. Because the inspectors know little about the inspection results at the time of the inspection, data collected often includes a significant amount of redundant points. To solve this problem, this study proposes the idea of applying autonomous robots to pavement inspections by utilizing the robot's features of mobility, high accuracy, and time and labor efficiencies. The robot will analyze the inspection data in real time, and plan the upcoming motion immediately. This helps us collect pavement data in a more effective way.

3. AUTONOMOUS ROBOT

An autonomous robot is an intelligent mechanical creature that can function autonomously. "Intelligent" implies that the robot does not do things in a mindless, repetitive way. The "mechanical creature" means that our scientific technology uses mechanical building blocks, not real biological components. It also emphasizes that a robot is not the same as a computer. A robot may have a computer as a building block, equivalent to a nervous system or brain, but the robot is able to interact with its world: move around in it and manipulate it. A computer does not move around of its own accord. "Function autonomously" indicates that the robot can operate, self-contained, under all reasonable conditions without requiring recourse to a human operator. Autonomy means that a robot can adapt to changes in its environment (the lights get turned off) or itself (a part breaks) and continue to reach its goal [8].

The general framework for a pavement inspection system is configured as shown in Figure 1(a). The conveyer (such as a vehicle) carries various inspection instruments and is controlled by an inspector in order to collect vast amount of data. Both longitudinal evenness (roughness) and transversal evenness (rutting) can be automatically and immediately analyzed during inspections. But, PCI computation has to be done at post-processing and relies on a computer. PCI computation takes the same (1:1) or more time than inspection. During inspections, inspectors are usually unable to know the results of the data being collected. They cannot adjust the inspection paths according to the inspection results in real-time. To avoid losing any important data points, the strategy they usually use is to collect all data points over all of the inspection area.

An autonomous robot consists of three parts, as shown in Figure 1(b): (1) a sensor unit; (2) an actuator unit; and (3) a logic unit [9]. The sensor unit works using instruments, such as an ultrasonic [10]/ laser range finder [11], image capture equipment [12], and an odometer in the pavement inspection system. The actuator unit [13] is responsible for robot motions and works as a conveyer in the pavement inspection system. The logic unit has computational power, which is similar to data analyses modules in the pavement inspection system. The logic unit is able to perform real-time computation and decision-making.

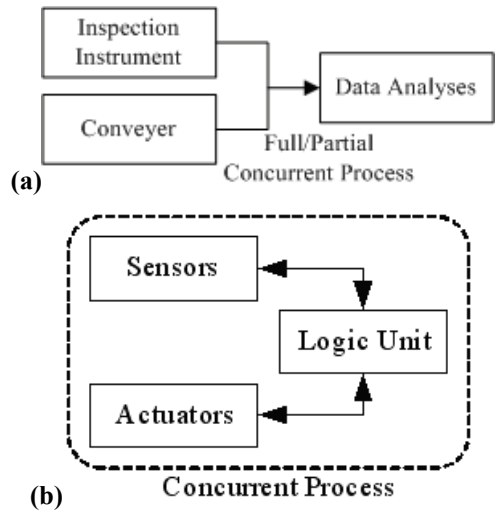


Figure 1 The Systematic Framework: (a) Present Pavement Inspection System; (b) Autonomous Robot

One autonomous robot framework for pavement inspections is proposed as in Figure 2. The sensor unit of the robot is combined with pavement inspection instruments and mounted on the robotic platform. By integrating the results from the logic unit of the robot and pavement data analyses, the robot is capable of intelligently planning the coming behaviors. Since the sensing and computing are synchronous, the time required for the processes of data collection and analyses can

be reduced significantly. The concurrent process also can reduce the data storage requirements.

4. ROBOTIC INSPECTION

Motion planning is one of the most important issues in developing a robot for pavement inspections. The major goal of the pavement inspections is to survey the overall pavement conditions and at the same time probe the pavement problems.

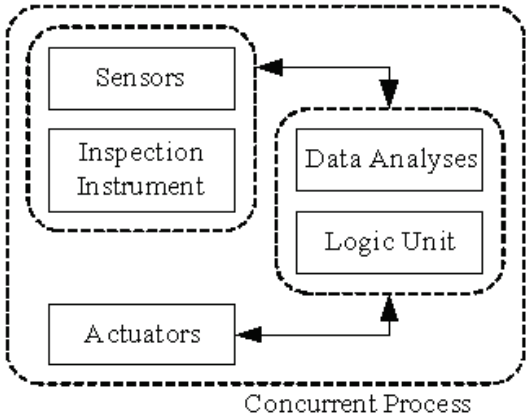


Figure 2 The Autonomous Robot Framework for Pavement Inspections

A typical scenario for pavement inspection is as follows. Given a predefined inspection area, the inspector has to run over this area at a certain speed. This speed is sufficient for the inspection instrument to obtain the information correctly. In the case of manual roughness inspection, for example, the inspector has to haul the walking profiler (a roughness inspection machine) along both wheel paths within the speed limit (< 800 m/hr). To plan the motion of the robot for the purpose of pavement inspection, we have to develop methods to define inspection paths. We also need to develop a method to ensure that the robot avoids all possible obstacles, including both static obstacles and dynamic obstacles. Additionally, a method for random inspection that enables the robot to run over the inspection area using a random procedure is also necessary if we would like to introduce intelligent sampling strategies for reducing the inspection time and the data storage requirements.

4.1 Motion Planning Methods

The authors proposed four motion planning methods: a transversal path planning method; a longitudinal path planning method; a random walk method; and an obstacle avoidance method, to enable robots to conduct pavement inspections autonomously. They are explained as follows:

- The *transversal path planning method* is to plan inspection paths that are perpendicular to the roadway. Because we assume the inspection area is given before the start of inspection, we can use a computer program to recognize the road boundary and generate the lines perpendicular to the boundary. By linking the lines, we are able to obtain a transversal inspection path.
- The *longitudinal path planning method* is to plan paths that are parallel to the roadway. Similar to the processes used in the transversal path planning method, we can generate the lines parallel to the roadway and find the longitudinal path by linking these parallel lines.
- The *random walk method* is to plan random movement for the robot. The basic technique is to assign random targets for a robot and ask it to move toward the targets consecutively.
- The *obstacle avoidance method* is a function that helps the robot avoids the obstacles in the physical environment. This method is achieved by continuously retrieving information from the sensors. When an obstacle is found, the robot will turn toward in the direction opposite to the robot's motion. In some cases, backward movement and random movement are also involved to avoid obstacles.

4.2 Robotic Pavement Inspection Paths

In this research, the authors proposed a method for robots to conduct pavement inspections. This method integrates the four aforementioned motion planning methods. We first target the scenario in which a robot conducts pavement inspection in a predefined environment with no obstacles. The only constraint for the robot's motion is the boundary of the inspection area. Then, we target a more complicated scenario, an inspection

environment that has random obstacles, which is closer to what the robot will face in the environments of actual pavement inspections.

Figure 3 shows four possible inspection paths for the first scenario: pavement inspection in a predefined and obstacle-free environment. Figure 3(a) illustrates the inspection path in a transversal mode. For the inspection task related to the transversal direction of a road, such as rutting (the pavement depression along wheel paths caused by tires), the robot may travel along the transversal path as shown in Figure 3(a). These paths can be generated by introducing the transversal path planning method. Figure 3(b) illustrates the longitudinal inspection mode. This mode is ideal for the inspections related to the pavement conditions along the roadway. Roughness inspection and distress survey are two such tasks. This path can be generated by introducing the longitudinal path planning method. Figure 3(c) illustrates a random inspection mode. The random walk motion planning method will facilitate the robot to conduct the random inspection when a sampling inspection is required. Figure 3(d) illustrates the grid mode for inspections. The robot either moves transversely or longitudinally. This mode can be an ideal solution for simultaneous inspections under the condition of roadway with irregular boundary. To generate the path, we can integrate both the transversal path planning method and the longitudinal path planning method.

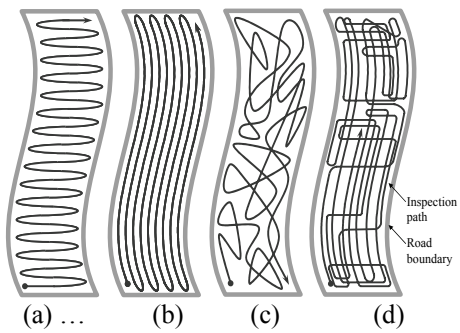


Figure 3 Pavement Inspection Paths Without Obstacles: (a) Transversal Mode; (b) Longitudinal Mode; (c) Random Mode; (d) Grid Mode

Figure 4 shows the scenario in which a robot conducts the inspection in an environment with randomly occurring obstacles. Figure 4(a) illustrates the transversal inspection in an environment with obstacles. By executing the path planning and obstacle avoidance methods simultaneously, we can see that the robot will follow the transversal inspection path in the region without obstacles. While the robot senses an obstacle, it will avoid the obstacle by slightly altering the path. After the obstacle region has been passed, the robot will continue following the predefined transversal path. Figures 4(b), (c) and (d) illustrate the simultaneous execution of the obstacle avoidance method and the longitudinal path planning method, the random walk method, and the combination of transversal and longitudinal path planning methods respectively.

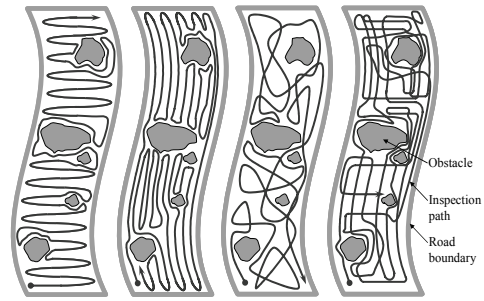


Figure 4 Pavement Inspection Paths With Obstacles: (a) Transversal Mode; (b) Longitudinal Mode; (c) Random Mode; (d) Grid Mode

5. SUMMARY AND FUTURE WORK

In this paper, we provided a method of using an autonomous robot to perform, what are for people, tedious pavement inspections. A framework that integrates the inspection instruments and the robot was proposed. The robot acts as an intelligent conveyer that carries the inspection instruments to conduct pavement inspections. We also proposed four robotic motion planning methods. They are the transversal path planning method, the longitudinal path planning method, the random walk method and the obstacle avoidance method. We illustrated how to integrate these motion planning methods to facilitate navigating the robot in both an obstacle-free environment and in an environment with random obstacles.

In the future, the authors plan to test the proposed methods in a simulation environment by using virtual reality technologies, such as Microsoft

Robotics Studio (MRS), to verify the feasibility of these methods applied to pavement inspections. If the virtual robot performs smoothly in the simulation environment, we will link the program to a real robot to extend our work into reality. Additionally, authors will provide some relative performance parameters in the use of robot when compared with a traditional pavement inspection method. The ultimate goal of this research is to develop a robot that is capable of conducting pavement inspections autonomously in an economical and intelligent way.

6. ACKNOWLEDGMENTS

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DEVELOPMENT OF AN AUTOMATIC FOUR-COLOR SPRAYING DEVICE CARRIED BY A ROBOT ARM

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ABSTRACT

Automation of building processes is the right mean to improve the average productivity of the construction industry, moreover in case of big and very complex projects. In addition the manufacturing of uniform high quality products can be pursued. This paper is concerned on an automatic system for interior wall painting, which is devoted not only to set an automatic spraying device on one six degree of freedom robot called "Pollock #1", but also to reproduce high quality artworks, using the same principles of four-color cartridges for printing machines. That end-tool was shown to be able to reproduce every color required by designers and, as a consequence, also drawings containing different chromatic scales, through controlling the movement of the arm with respect to the changeable colour mix sprayed by the end tool. Finally, an accurate and efficient automated methodology to reproduce colored drawings from their graphic digital format to their final application on building walls is presented.

KEY WORDS

Multicolor Painting Robot, Construction Robot, Miniature Laboratory, Scaled-Down Laboratory.

1. INTRODUCTION

In this paper a 1:4 scaled down robotized painting end-tool for robots is developed, in such a way that it has the same capabilities of presently marketed colour printing machines, while being able to work in job sites. As it is thought for the industry of construction, its features must be considerably different from the ones used for painting in the automotive industry, or for furniture painting.

There are a lot of factors that can justify the adoption of robots in the construction industry; they are generally roughly divided between [1]:

- improve productivity and save human labour;
- allowing higher quality standards of products.

The first item encompasses on one side the purpose of better management of the whole construction process (lowering time and resource usage for higher incomes) and on the other side the possibility to eliminate human exposure to difficult and hazardous environments, improving the quality of work for employees in the construction industry. However this paper is devoted to the second item: thanks to the specific capabilities of automated machines (e.g. high speed, high precision and accuracy) it is possible to realize artworks that could not be otherwise manufactured through the use of human standard skilled workers, at the same or lower prices than traditional wall painting (with the exception of raw materials and of the more complex device for execution). In other words, it is just necessary to buy more than one colour (three or four depending on the drawing to be reproduced) and to be equipped with the device presented in the following, in order to be able to make wall drawings using the same technique presently used by printing machines for paper printing. In fact we are developing a printing machine for wall painting in buildings, but which needs to be appropriately coordinated with automatic technologies for robotics. This original system can be carried by robots throughout work sites, representing an interesting step forward with respect to all the other non-mobile spraying tools for painting used in industrial chains.

After a preliminary introduction on the main problems connected with spray painting, this paper presents our findings about the manufacturing of an original spraying tool, which is able to manage a four-color (in this paper a three-color application has been experimented) air-mixing device; then it has been mounted on a six degree of freedom robot arm and used during a very successful experimental campaign, that ends up with a novel procedure for artworks' colours reproduction from digital graphic information.

2. DESIGN OF THE SPRAYING TOOL

2.1. State of the Art

The first spraying nozzles date back to the second and third decade of the last century, when they were used in the automotive industry. Instead the first example of pneumatic spraying robot was installed in 1964 by ABB Tallfa Company [2], which was just the prototype of a successful series of more recent devices for industrial chains. On the contrary, not many robots are known in the building sector, and none of them is highly autonomous. The robotic system for bridge maintenance in [3] can be classified as a semi-autonomous robot, because it allows the automated execution of all the operations that would be dangerous when executed by human labor hung under the bridge, but it requires supervision by one or more operators from a safe place on the bridge. Automation is concerned with the robot's capability to make inspection of the bridge, washing, old painting removal and new painting through the use of sensors. However, in order to make painting robots economically convenient for construction, they must be totally autonomous, which is the target of a number of research projects that are presently going on. This argument is presented in [4], where the multipurpose robot TAMIR was used to show how considerable can be savings in labor. But it is in [5, 6] that TAMIR was used to make further experiments with painting: through full scale experiments it was shown that, according to the break-even point technique, robots are always more profitable than human work when highly autonomous machines are adopted. Given this premise, it is advisable to exploit also another feature of automation: its capability to perform high quality works, that should allow to give back high quality final products otherwise not obtainable with the usage of just human labor. In the particular case of this paper we will analyze the possibility to reproduce drawings on interior walls, in the same way it is made by printing machines on paper sheets.

2.2 The Experimental Approach

The work in this paper was carried out in the same laboratory described in [7]. The final aim is supporting a fast development of this technology through the use of a 1:4 scaled-down laboratory, which requires less availability of raw materials, electronic costly equipments and human efforts. Particular attention is devoted to the scaling process from full size to the reduced one, for reproducing actual environments of construction sites.

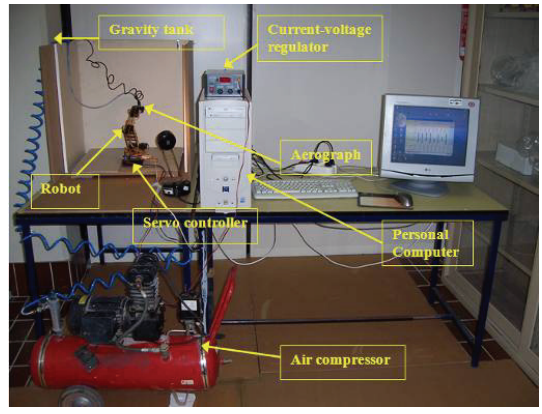


Figure 1 The 1:4 Scaled-Down Laboratory

Figure 1 shows the main components of this small laboratory: one current and voltage regulator (range from 0 to 12 V and from 0 to 6 A); small plaster made surfaces to simulate some building walls mounted on three sides; one 6 degree of freedom robot (Pollock #1) controlled by a 32 channel servo controller connected to the serial port of a PC, having a nominal reach of 0.4 m and a play load of 40 N; one compressor to send high pressure air flow towards the aerograph fed by a tank, which have been modified in the way developed over the next paragraph to allow it to draw multicolor paintings.

2.3 The Painting End-Tool

Every elementary painting equipment is made up of at least the following components: one spray

gun, a tank containing paint and a device to lead paint out the tank and send it to the spray gun. There are also three main approaches for painting: Airless; Aerography; Airmix.

The airless painting system works at very high pressure: paint is sent to the spray gun at about $1.2 \cdot 10^6$ Pa (to be created by a pump), whose precise value depends on its physical and state characteristics (density, viscosity, temperature, surface tension, solvent volatility, speed). In this case the jet stream shape is uniquely determined by the nozzle slot, which is generally chosen as vertically oriented. Instead the flow rate of paint is determined by the nozzle extension, which is generally limited from $3.1 \cdot 10^{-8}$ to $1.7 \cdot 10^{-6}$ m^2 [8]. Paint flows through the nozzle at an average speed of about 140 m/s and it is held at about 0.25 m from the wall. Instead aerography produces a jet where air is mixed with paint, which is in turn sucked by air into the gun. It is different from the airless type, that directly atomizes paint through high pressures; in this case paint is sucked by high pressure air (about $4 \cdot 10^4$ Pa) flowing through the spray gun towards the nozzle. Sometimes the gun is fed by gravity or by low pressure, in order to help paint to pass through the gun, but the principle does not change, because in this second case high pressure air is always in charge of paint atomization. This technique is older than the previous one but is not suitable for quick drying paints and produces bigger drops and thicker films, hence lower quality products. In addition, its application is not simple because it generates a paint cloud around the nozzle and it could be dangerous for workers. The airmix system tradeoffs between the two former possibilities, and it is very useful for high precision works. It is practiced through a nozzle that has three holes: one in the centre working in airless mode; other two holes on the sides blowing high pressure air to mold the whole paint jet into the desired shape. Paint is blown between 3 and $6 \cdot 10^5$ Pa, and air is tuned according to the wished final result, whose pressure's magnitude is lower than for aerography (generally between 1 and $3 \cdot 10^4$ Pa).

The possibility to develop a multicolor system for buildings is new: it would revolutionize the concept of building painting and moreover its process. Similar applications are known just in the industrial field: they basically use very heavy paint distributors, which would be difficult to move [9]. Moreover, they mix colors inside the distributors, which is far from the nozzle, requiring long time delays to switch from one color to another. From Fig. 2 it can be inferred that it is important to locate the mixing system as close as possible to the spraying nozzle, in order to quicken the switching.

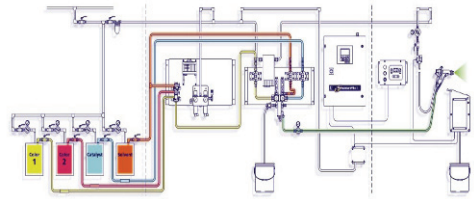


Figure 2 PrecisionMix™ System Delivered by Graco

2.4 The Carrying Robot-Arm and the Whole Experimental Set up

Considering the necessity to tune the shape of the spraying jet according to the size of walls and also the necessity to make experiments in the small laboratory, it was decided to develop a scaled-down airmix spraying gun, whose full scale reproduction can be straightforward. Fig. 3 shows the functioning of the system to be realized: the four primary colors have been put inside high pressure tanks to be sent to the mixing board, which turns up or down their relative amount, previous to their blending into the mixing device close to the gun. Even if it has been designed for four colors, however all the experiments have been performed with three colors: cyan, magenta and yellow. Before showing the whole experimental set up it is necessary to understand how the mixing board in Fig. 4 works. The four color tanks push paint towards the mixing board at high pressure of $1.5 \cdot 10^5$ Pa, which is equipped with four ball valves. Every valve is connected to a servo (deflecting torque equals to 0.132 $kg \cdot m$) which turns up or down the amount of paints flowing through it, establishing the percentage of primary colors to be mixed in the following device and hence deciding the hue of the final color.

Every servo is driven by the same controller of Pollock #1, such that colors are coordinated with the robot's movements. From the mixing board the primary colors move towards the mixing device in Fig. 5-a, which is a hollow aluminum

parallelepiped containing one transversal positioned steel spiral, helping the colors to be mixed into the final one. This device is very close to the spraying gun (Fig. 5-b), that is the place where paint is mixed with air flowing at $3.5 \cdot 10^5$ Pa and then atomized while being sprayed. In Fig. 6 we can see all the experimental equipment, mounted in the scaled-down laboratory.

3. PRELIMINARY EXPERIMENTAL CAMPAIGN

First experiments have been made to verify that 1:4 scaling of the distance between the gun and the wall gives back good results when the moving speed is between 0.8 and 1.5 m/s. Then other trials have been devoted to the determination of the following parameters: optimum paint flow rate through the nozzle; optimum paint flow rate through the ball valves of the controlling board. As far as the flow rate through the nozzle, five controlled experiments have been executed, and finally its average optimum value has been computed to be equal to $3.4 \cdot 10^{-7}$ m^3/s. For the sake of understanding the behavior of the ball valve, its characteristic curve describing the paint flow rate with respect to its rotation around its axis from the closed position has been drawn. The valve has been turned on through steps of 15 degrees, and the corresponding flow rate has been measured as pictured in Fig. 7. The relation coming out from Fig. 7 is of basic importance: thanks to that, the controller will be able to compute the required opening of each valve to obtain some pre-established final color starting from the primary ones. It knows that at every step the relative flow rates must be linked by the relation:

$$1 = \frac{Q_C}{Q} + \frac{Q_M}{Q} + \frac{Q_Y}{Q} \quad (1)$$

Where Q is the total paint flow rate, while Q_C, Q_M and Q_Y are the flow rates assigned to each primary color. From the theory of color explained in the next paragraph it is possible to compute every relative flow rate and then the relation in Fig. 7 can be used to compute the required opening for each valve.

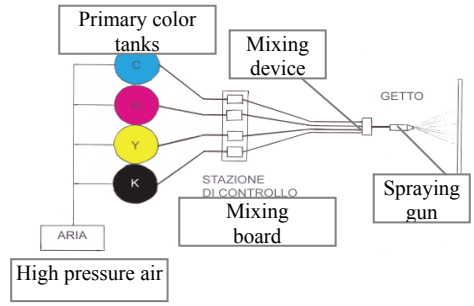


Figure 3 Sketch of the Final Multicolor Airmix Device

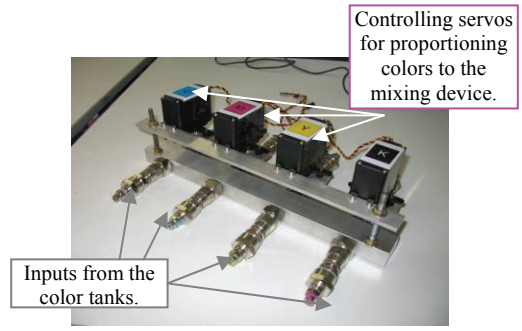


Figure 4 Mixing Board

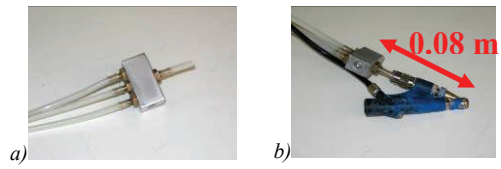


Figure 5 Mixing Device (a) and Spraying Gun (b)

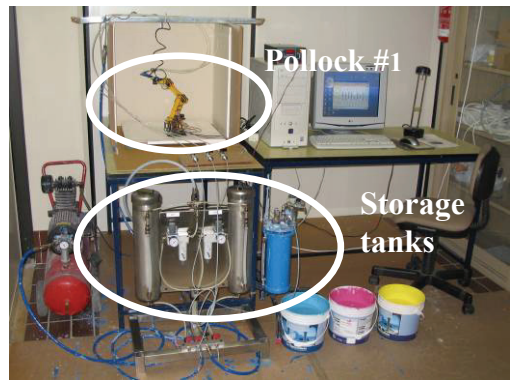


Figure 6 Whole Experimental Equipment

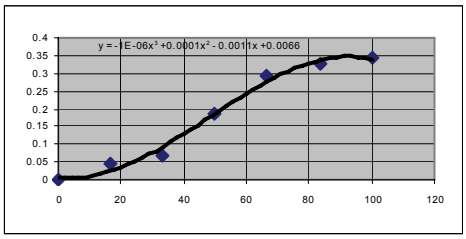
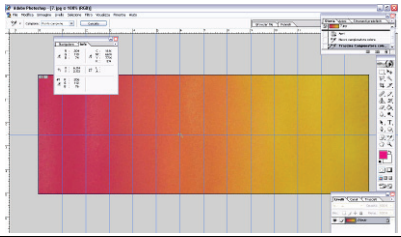


Figure 7 Characteristic Curve of the Ball Valves

Finally, other two trials have been made: analysis of precision and time delay connected to color switching.



Mean	86	84	83	79	71	68	63	58	54	47	41	36	35
Stand. Dev.	2.5	3	2	2.9	4.4	3.3	4.4	4.1	6	7.5	5.3	5.1	7.3
% Stand. Dev.	2.9	3.5	2.4	3.7	6.1	4.9	7	7	11	16	13	14	21

Figure 8 Precision Evaluation

The first analysis have been made by generating a sample of size 9, formed by nine shaded portions of walls of the kind in Fig. 8, from magenta to yellow and other 9 from cyan to magenta. Through a software for imaging processing, the saturation of each sample on a 14 equally spaced column grid has been measured. In Fig. 8 we can appreciate that on each point of the grid, standard deviation measured for magenta on the selected points are low, and on the average equal to 8%. Similar good results have been obtained for the other two primary colors. The time delay has been measure by filming the movements of the servos on the mixing board and the colors sprayed on the walls: the time difference between color switching of the ball valve and the time when it is observed on the wall is the unknown time delay. It has been found out to be equal to 3 s (this time have been considered in the control algorithms used by the controller during painting).

4. A FIRST PROCEDURE FOR REPRODUCTION OF DRAWINGS

One of the most important requirements for such a system is that it can accurately reproduce the colors of every pixel of drawings. For that purpose a general procedure for color reproduction has been set, that is based on the theory of colors [10, 11]. As we are dealing with a system working like printing machines, every color can be thought as composition of the three primary ones: cyan, magenta and yellow (generally also black is included to obtain a wider range in the visible spectrum, however in this experiment it was neglected). We will explain the general procedure while applying it to one real case. First of all a color belonging to the visible spectrum has been generated with the help of a software for image processing (Fig. 9-a), having the following normalized coordinates (C,M,Y) = (0.43,0.06,0.51). Every normalized coordinate is computed from the original CIE (Commission Internationale de l'Eclairage) coordinates (c,m,y) by defining:

$$C = \frac{c}{c + m + y} \tag{2}$$

and the same holds for magenta and yellow. Then it must be considered that the primary colors used by our system are not the same primary colors considered by the image processing software. Hence three wall samples have been painted using these primary colors and obtaining the following normalized coordinates:

1st primary color (C*) = (0.67, 0.2, 0.13);
2nd primary color (M*) = (0.12, 0.80, 0.08); (3)
3rd primary color (Y*) = (0.05, 0.00, 0.95).

The relative amount of the system's primary colors (C^*,M^*,Y^*) to be used for the reproduction of the original color (C, M, Y) have been computed by solving the following system:

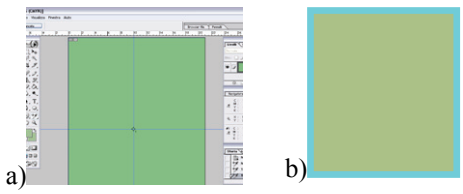
$$\begin{cases} C^* + \alpha_c M^* + \beta_c Y^* = C \\ \alpha_M C^* + M^* + \beta_M Y^* = M \\ \alpha_Y C^* + \beta_Y M^* + Y^* = Y \end{cases} \tag{4}$$

Where the coefficients α and β allow for the non purity of our primary colors. For instance, if we know that the system must spray a certain amount of cyan (C), it is present not only in its cyan (C*) but has also other contributions in its magenta (α_c=12% and β_c=5%), as suggested by eq. (3), from which all the other coefficients have been

determined. The unknown variables have thus been determined to be (C*, M*, Y*) = (0.476, 0.025, 0.54). Then applying eq. (1) in the following form:

$$1 = C^* + M^* + Y^* = \frac{Q_C}{Q} + \frac{Q_M}{Q} + \frac{Q_Y}{Q} \quad (5)$$

And by the knowledge of the optimum flow rate Q, it was possible to compute the single flow rate values Q_C, Q_M and Q_Y; from these values and from the diagram in Fig. 7, valves' openings were determined and the final color was sprayed on a plaster wall sample (Fig. 9-b). Observing the two figures it is possible to appreciate that they are very similar.



a) b)

Figure 9 Original Color (a) and its Reproduction Through our System (b)

But this check has been performed also using a scanner acquisition system: it gave back the normalized values (0.53, 0.58, 0.31) for Fig. 9-b, which have been corrected by the knowledge of the shift introduced by that scanner (previously determined scanning pure primary colors from [11]), that is (+0.20, +0.06, -0.26). Hence the corrected value of the color sprayed by our system was (0.33, 0.1, 0.57), whose difference with the original one is (-0.1,+0.04, +0.06), that is the approximation introduced by the whole mechanical system.

5. CONCLUSIONS AND FUTURE RESEARCH

Thanks to the mixing equipment developed throughout the research step described in this paper, we have shown that automated painting can be not only aimed at improving productivity, but also quality. The next step will require re-scaling back of these results to full scale and further studies for development of control algorithms that could allow reproduction of more complex graphic patterns. Those experiments will be useful also to discern the limit of accuracy that can be pursued by such a system, depending on the variation of some parameters like time delays connected to switching.

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A SELF-ASSEMBLING CURTAIN WALL SYSTEM

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ABSTRACT

Robots are only incidentally used to assemble wall panels in high-rise buildings, even though robotic technology is available for various applications. These applications can improve construction site safety and increase the productivity of the assembly process. A research project initiated at Eindhoven University of Technology (TU/e) in the Netherlands aims to develop an integral design for a curtain wall. The curtain wall's assembly, disassembly and user functions are integrated into a single concept. The focus lies on the assembly/disassembly process and the use of new robotic technology.

This paper presents the further results of a concept design based on the requirements found in an earlier survey of currently available strategies for the assembly of curtain wall systems. The purpose of this research project is to explore the limits of currently available robotic technology in designing a curtain wall for its entire life cycle by integrally designing a feasible concept.

KEYWORDS

Curtain Wall System, Wall Panels, Robot Technology, Construction Site Safety

1. INTRODUCTION

As a rule, the conditions under which the panels of a curtain wall system for high-rise buildings are assembled and disassembled are neither safe nor labour-friendly. Moreover, climate conditions can make production time uncertain. See figure 1.

New robot technology and materials can help to solve the problems identified above, while this technology can also be used for other wall functions such as sunscreens, ventilation and cleaning.

The application of new robot technology requires the integral design of the assembly process, the curtain wall and the wall panels.

In a previous study [1], the design requirements for a curtain wall that is self-supporting during its entire life cycle were developed. The design requirements formulated in the conclusion of that study included the following:

- Safe construction site for assembly workers.
- Curtain wall is appropriate for high-rise constructions involving a steel load-bearing construction.
- The curtain walls are only made of aluminium and glass.
- The curtain wall is equipped for the assembly and disassembly processes. Its components can also be used for user functions (particularly systems) of the façade element.
- Only one remote operator is necessary for the (dis)assembly process.
- Mini- and micro-robot devices are used.

The goal of this study is to develop a concept for a self-assembling curtain wall system that is safe, labour-friendly and can be used in all weather conditions (e.g. wind, rain, snow) without a construction crane being needed and with as few

construction workers as possible. The concept is based on the design requirements as formulated above.

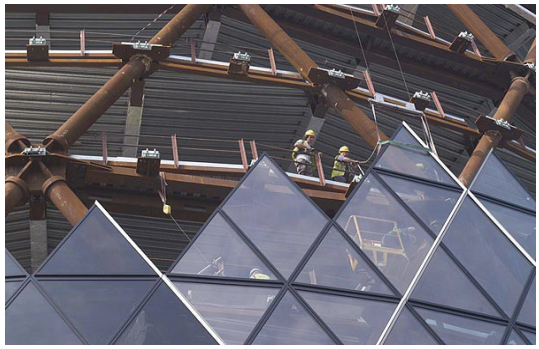


Figure 1 Curtain Wall assembly can be Extremely Dangerous. Photo showing the assembly of the wall panels for the St. Mary Axe high-rise building in London (Photo: Grant Smith)

2. DESIGN METHOD

The followings steps were carried out to design the new concept:

1. Re-formulating the requirements.
2. Analysing the problem.
3. Designing the concept by using morphologic schemes and Systematic Inventive Techniques (SIT) [2].
4. Engineering the concept.
5. Creating a 3D virtual simulation of the assembly process.
6. Reflection by experts.

3. RESULTS

3.1 Re-formulated Requirements

Curtain wall:

- Application of panels that are produced in the factory,
- Standard frame with customised filling,
- Wind and water sealing,
- Every panel can be individually assembled and disassembled,
- The drive can also be used for other functions.
- Even design.

Transport of panels to assembly location:

- Self-transporting,
- Self-positioning,
- Motor-driven,
- Constructed from the ground floor of the construction site.

Assembly panel:

- No labour,
- Assembly onto an existing structure

3.2 Analysing Some Aspects of the Problem

Before forming a concept, some specific aspects required special study:

- Transport of the panels. After studying various alternatives, a choice was made to only transport (during assembly and disassembly) the panels vertically.
- The mounting of the panels at the structure. There is no connection between the panels other than some loose connections for water and wind sealing; it must be possible to mount and dismount any panel at any time.
- The start of assembly. There must be a basis with which to start the automatic assembly process. The first row of panels will be placed with the help of a crane. See figure 2.

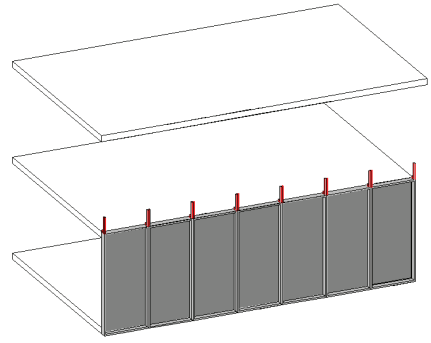


Figure 2 The First Row of the Curtain Wall will be Placed with the Help of a Crane

3.3 Assembly Concept

The assembly concept comprises six steps:

1. Assembling the first row as mentioned in the previous paragraph. A mounting component is also placed on every floor of the structure.

2. A crane will place a new panel onto a panel in the first row. To keep the panels in position, a guide mechanism and a T-profile are mounted beside the panel.
3. The vertical transport of the panel occurs with the help of a gearwheel driven by a motor and a gear rack.
4. A guided stand is mounted on top of every panel to keep the panel in place.
5. The panel can now be transported horizontally to the structure. The gear rack moves via the mounting component.
6. The element is now in its final position. An operator will fix the panel.

Table 1 describes the six steps of the assembly concept.

3.4 Engineering

A series of details have been designed to solve engineering problems. This paper will explain some of them.Water and wind sealing is solved with the help of synthetic profiles, which are mounted in the factory and automatically close the spaces between the panels after placement. See figure 4.

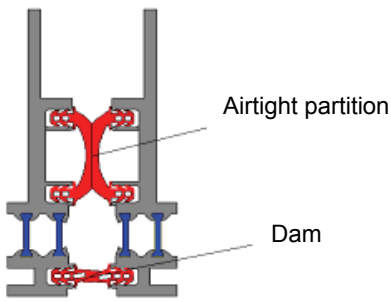


Figure 4 Upper Profile for Air Sealing and Lower Profile for Water Sealing

A mounting component is placed at the edge of the floor-slab. This component will realise the horizontal transport of the panel by a gear rack, placement by a buckle and locking by a pin. See figure 5. The driving section. An electric motor, shaft, chains and gear wheels are mounted in the panel. See figure 6.

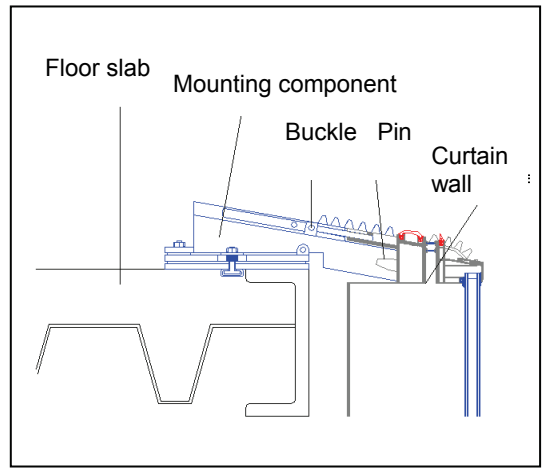


Figure 5 The Mounting Component

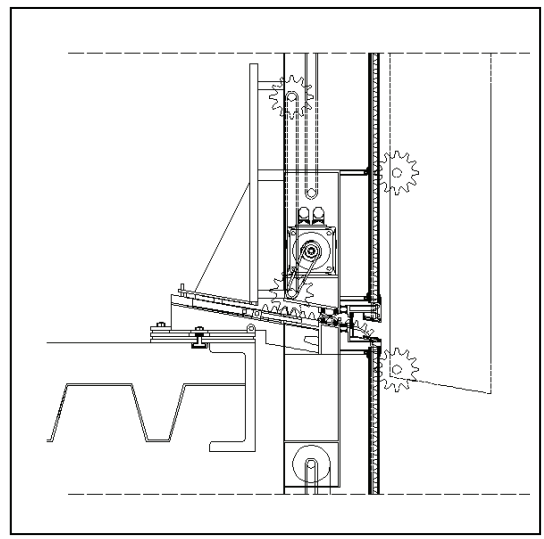
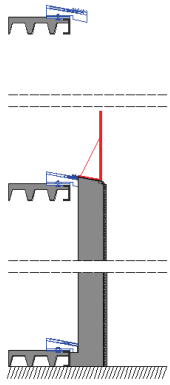
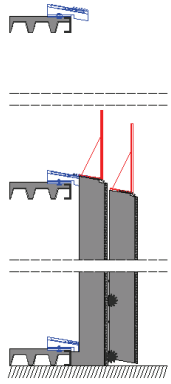
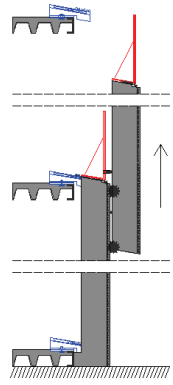
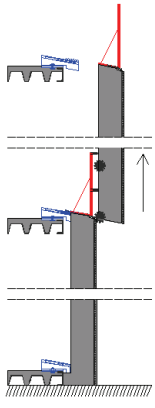
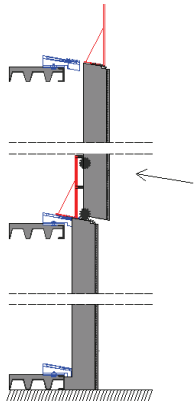
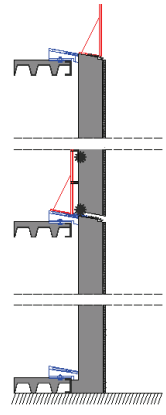


Figure 6 The Driving Section of the Panel

Frame and filling. The wall panel consists of a frame and a filling.

All the mechanisms for transport and placement are built into the frame. This enables mass production and mass customisation.

Table 1 The Assembly Process in Six Steps

		
1. Assembling the first row. A mounting component is also placed on every floor of the structure.	**2.** A crane will place a new panel on a panel in the first row. To keep the panels in position, a guide mechanism and T-profile are mounted on the panel.	**3.** The vertical transport of the panel occurs with the help of a gearwheel driven by a motor and a gear rack.
		
4. On top of every panel is a guided stand that will keep the panel in place.	**5.** The panel can now be horizontally transported to the structure.	**6.** The element is now in its final position. The stand remains as part of the façade.

The filling can be chosen by either the client or the architect and can be designed as a modular system.

3.5 Simulation

To get more of an idea of the assembly process and how it will work in reality, a 3D virtual simulation has been made.

3.6 Reaction from Experts

The concept was presented to two professionals in the field of façades.

One reaction was that 'One of the plus points of this concept is the guided transport system, which ensures that wind has no influence on the mounting process, which is an advantage when building very tall buildings. Instead of a built-in electric motor, a little crane could also be a solution'.

However, there was doubt as to whether there is a market for robotic technology for such façade facilities as ventilation.

The firm found the integration of the electric drive and the positioning very interesting, but the question remains as to when the costs are acceptable for the client and the architect.

The Dutch knowledge centre of façade builders found the concept both interesting and innovative, but some aspects, such as the reliability of the guidance system and water and wind sealing, remain uncertain. Using the drives for transport is a positive factor, as is the user functions facility, because this gives greater façade flexibility, especially in case of renewal.

4. DISCUSSION

The results have shown that most of the requirements have been fulfilled, although some requirements with regards to self-assembly of the entire curtain façade have not.

The ultimate goal of eliminating the work of the construction worker was not feasible, as they are still needed to mount the panels on the ground floor and to undertake some simple mounting operations during the assembly process as a whole.

Various parts of the concept have not yet been tested, such as wind and water sealing, gear transmission and guide rails.

The cost of the driving motor is relatively high and has too much power output for such wall functions as ventilation and sunscreens. One solution would be to use a replicable motor.

5. CONCLUSIONS

The introduction listed various problems concerning the assembly and disassembly of curtain wall panels. With this concept, (dis)assembly work is safer and more labour-friendly, and weather conditions have less influence on the progress of the construction work.

Furthermore, the concept allows for using the electric drive for sunscreens and ventilation.

The concept has the potential to solve the problems of labour safety and bad weather conditions that occur when mounting panels.

The concept gives us more insight into how to use robotics and robot technology as for assembly at the construction site and for other wall functions such as ventilation and sunscreens.

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DESIGN OF A CEILING GLASS INSTALLATION ROBOT

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ABSTRACT

Building materials and components are much larger and heavier than many industrial materials. Ceiling glass is a type of building material for interior finishing. The demand for larger ceiling glass has increased along with the number of high-rise buildings and an increased interest in interior design. The objective of the study is to introduce robotic technology for installing ceiling glass on construction site. Robotically installed ceiling glass is receiving special attention because of the difficulties in moving to high installation positions and handling fragile building materials. Below, we describe the design of a ceiling glass installation robot. After analyzing a target project, we establish a design concept for a proposed robot. Finally, we describe the detailed design of the robot.

KEYWORDS

Ceiling Glass, Installation Robot, Hardware Design

1. INTRODUCTION

The importance of applying the "Automation System and Robotics in construction" has been raised, as a result of the need for improvement in safety, productivity, quality, and the work environment [1], [2]. Consequently, operations involving automation systems and robots are widely found at construction sites. Since the late 1980s, construction robots have helped operators perform hazardous, tedious, and health-endangering tasks in heavy material handling. Iwamoto et al. stated a similar problem that reduces the need for a labor force and provides improved productivity and safety [3]. Isao et al. discussed the appropriateness of the automation technology for installation of a curtain wall [4]. Masatoshi et al. proposed the automated building interior finishing system, and a suitable structural work method is described [5]. Lee et al. developed an automation system (ASCI; Automation System for Curtain Wall Installation) that is suitable for mechanized construction, which enables simpler and more precise installation than existing construction methods, while improving safety during installation [6].

Robots can be classified into two groups: those that can carry out work and coexist with humans in atypical environments, and those that do repeated work according to a standard program such as part assembly or welding and coating in the automobile and electronic industries. Thus, manufacturing robots are stationary and the product moves along an assembly line. In contrast, construction projects require a stationary product, that is the building, and the robots change location. Moreover, in manufacturing, robotic repetition provides identical products, whereas, in construction, the product is custom-made and robots must be reprogrammed to operate in each given condition [7]. Consequently, construction robots are defined as field robots that execute orders while operating in a dynamic environment where structures, operators, and equipment are constantly changing. Therefore, a guidance or remote-controlled system is the natural way to implement construction robot manipulators.

Building materials and components are much larger and heavier than many other industrial materials. Buildings are made of many kinds of materials and each material may be a different shape. Ceiling glass is one type of building material for interior finishing. The demand for larger ceiling glass has been increasing along with the number of high-rise buildings and the increased interest in interior design. The objective of the study is to introduce robotic technology for installing ceiling glass on construction site. Ceiling glass installation robots are receiving special attention because of the difficulties of transporting the glass to high installation positions and handling the fragile building material. In order to address these conditions, the form of a ceiling glass installation robot is different from other construction robots.

A discussion follows that describes the design of a ceiling glass installation robot, which is introduced to address the above problems. After analyzing a target project, a concept design was produced for the proposed robot. Lastly, a detailed design of the robot is described, which is based on the concept design.

2. ANALYSIS OF TARGET PROJECT

The existing ceiling glass installation process, which is complicated and hazardous, relies on scaffolding (or aerial lift) and human labor. This process exposes operators to falling accidents or vehicle rollovers. In addition, inappropriate working posture is a major element that increases the frequency of accidents by causing various musculoskeletal disorders and decreasing concentration [8]. That is to say, it becomes a direct cause of decreasing productivity and safety in construction.

Figure 1 shows the construction site and ceiling glass installation position (soffit of building) related to this study. The building size is 32m × 22m and the installation position of the ceiling glass is 7.9m above the ground. Ceiling glass used for installation is classified into two categories. The first category is ceiling glass that has 1500mm × 1500mm dimensions and is 80kg. The second category is ceiling glass that has 750mm × 1500mm dimensions and is 40kg. This paper introduces the 'Module T&H-bar' installation method, which represents the 'Lay-in' to place the ceiling glass on ceiling frames.

According to analysis of the target project, it is deduced that the functional needs for implementing a ceiling class installation robot are as follows:

- The ceiling glass installation robot must be able to lift heavy ceiling glass, an operator, and the installation equipment. It requires engines, batteries, or motors to lift the weight.



Figure 1 Construction Site and Installation Position

- The ceiling glass installation robot must be able to handle heavy and fragile ceiling glass. It requires sophisticated force and position control including human-robot cooperative control. That is to say, the operator must be able to perceive external information that is received by the robot.
- The ceiling glass installation robot must be devised to help operators, not to replace them. This requires a smart HRI (Human Robot Interface) to interact with operators and robots. The robot must share the work space with an operator.
- The ceiling glass installation robot must be able to reflect the technical operator's skills that are required to obtain homogeneous construction quality. Thus, the robot must follow the operator's intentions in various environments at unstructured construction sites.
- The ceiling glass installation robot must belong in the working process. This is required to prevent operator accidents and help operators increase productivity, by reducing the recovery time from accidents and increasing the operator's duty time.

3. CONCEPT DESIGN

The development methods for construction robots can be classified into two categories. The first category involves developing entirely new robots that can achieve requested work. The second category involves new robots implementing existing systems. The first method is beneficial in optimizing specifically requested work. However, the cost and time required by this method are the major drawbacks to developing new robots. The second method is difficult to optimize for target projects, but it can achieve efficiency with limited cost and time requirements. In this study, the second method is introduced to develop the suggested robot.

According to analysis of the functional requirements, a concept design was generated, which will influence the suggested robot.

- An aerial lift is needed that can support heavy ceiling glass, an operator, and the installation equipment with enough work space to reach about 7.9m above the ground.
- A multi-DOF manipulator is required to install heavy ceiling glass, which replaces a large mount of human labor. The manipulator has to be chosen according to work space and payload.
- This robot is a semi-automated system to cope with a constantly changing work environment. Thus, the robot works and coexists with operators in atypical work conditions. The operator uses the multi-DOF manipulator from the deck of an aerial lift.
- The gripper is based on vacuum and mechanical devices, while the ceiling glass gripping is performed manually.
- After gripping the ceiling glass the manipulator is operated by an operator. An operator supplies external force containing an operational command on the HRI device. Therefore, the manipulator can be controlled by an intuitive installation method that can reflect the dexterity of a technical operator.
- The deck of an aerial lift serves simultaneously as an operator's work space and a manipulator. Therefore, the operator's safety and productivity is influenced by the design of the deck.
- The control strategy of the suggested robot is a combination of the force applied and the robot.

Figure 2 shows a schematic of the ceiling glass installation robot that was determined by analyzing the concept design.

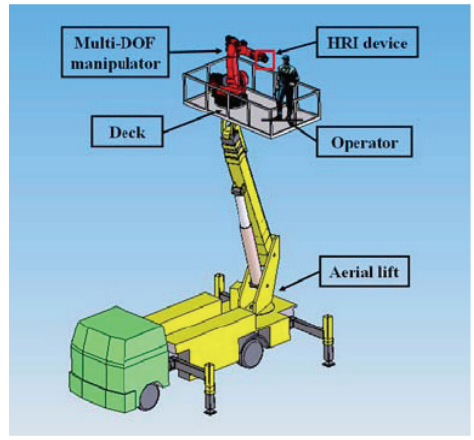


Figure 2 Schematic of Ceiling Glass Installation Robot

4. DESIGN OF ROBOT SYSTEM

The hardware design of the robot system is classified into three parts: an aerial lift, a multi-DOF manipulator, and an HRI device.

4.1 Aerial Lift

Aerial lifts are designed for enabling altitude work. In this study, the aerial lift raises the manipulator, ceiling glass, and an operator up to 7.9m. A discussion follows concerning the selection of the aerial lift and the design of the work deck.

In selecting a suitable aerial lift, diverse aspects were considered including mobility, reachable distance, and payload. The aerial lift must have adjustable movement within a constantly changing work environment. Therefore, considering mobility, a wheel type of aerial lift was selected, which is mounted on the truck with a telescopic boom.

Considering the reachable distance and payload, it is necessary to expand the selection criteria to include not only specific properties but also safety concerns. Table 1 shows the specifications for the selected aerial lift. The rotation range is related to a base coordinate system {O}, as shown in Fig. 3. In order to implement automated lifting, the kinematic analysis of the aerial lift (RRPRR type manipulator) must be considered, as shown in Fig. 3 and Table 2.

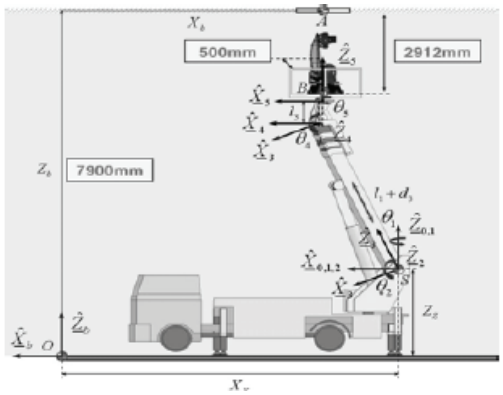


Figure 3 Coordinate Systems of the Aerial Lift

The design of the aerial lift deck is important to serve as the work space of an operator and a manipulator, in order to increase productivity and safety. When ceiling glass pieces, an operator, and the multi-DOF manipulator are lifted by the aerial lift, the position of ceiling pieces and the manipulator on the deck influences the operator's allowable movement.

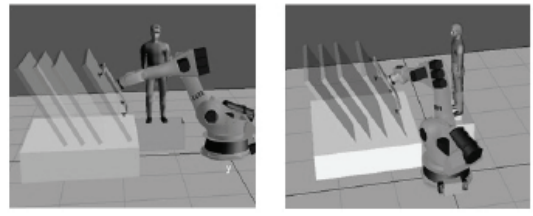
Table 1 Specifications of the Selected Aerial Lift

Items		Details
Max. payload		2000kg
Boom	Rotation range (Y axis)	-17~70°
	Rotation range (Z axis)	360°
	Max. working radius	5~7m
Outrigger		H type
Width (set outrigger)		4.2m

Table 2 D-H Table of the Aerial Lift

i	$_{1i}\alpha$ –	$_{1}a_{i}$–	d_{i}	$_{i}\theta$
1	0	0	0	$_{1}\theta$
2	/2π	0	0	$_{2}\theta$
3	/2π–	0	$_{1\ 3}ld$+	0
4	/2π	0	0	$_{4}\theta$
5	/2π–	$_{2}l$	$_{3}l$	$_{5}\theta$

Moreover, the deck shape must be optimized to increase operation dexterity, in order to avoid obstacles and allow for a smooth approach to the target position. Two cases were proposed concerning the position of the ceiling pieces, as shown in Fig. 4. After simulating the operation's movements and manipulator's operation, it was found that case 2 requires more motion by the manipulator than case 1, and needs a larger work space than case 1. Therefore, case 1 was selected, in which the ceiling glass is positioned in front of the manipulator on the deck, as shown in Fig.5. The operator's body size was considered, in order to prevent WMSD (Work-related Musculo-Skeletal Disorders), as shown in Figure 6.



(a) Case 1 (b) Case 2

Figure 4 Simulations for Deck Design

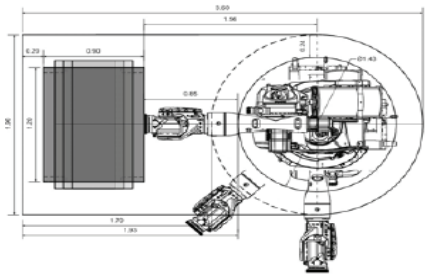


Figure 5 Simulations for Deck Design

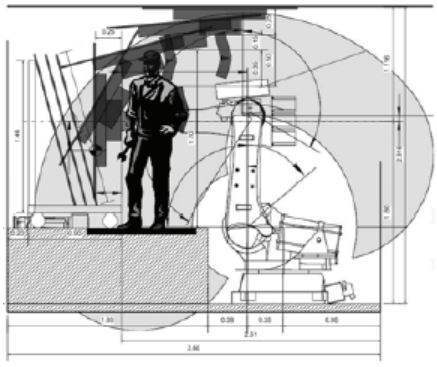


Figure 6 Simulations for Deck Design

4.2 Multi-DOF Manipulator

A multi-DOF manipulator is needed to install heavy ceiling glass, thereby replacing a large amount of human labor, by correlating the operator and manipulator. The manipulator is chosen to help the operators, not to replace them. The manipulator has to be chosen according to the work space and payload. The payload and the weight of any additional devices (vacuum suction device, HRI device) required for installation must be considered. Figure 7 and Table 3 show the coordinate systems and D-H table for the selected model (KUKA Industrial Robots), respectively. In order to control the motion of the manipulator, kinematic and dynamic analysis is required. As operator's safety is influenced by these types of motion, while any singularities in the hardware should be considered carefully.

The design of a vacuum suction device includes the position of the vacuum suction pads, available payload, and the weight of itself. A section of the vacuum suction pads should be designed in accordance with the width of the smallest ceiling glass. Four vacuum suction pads were used, in which each suction cup can support up to 60kg. The vacuum suction pads are positioned in aquadrilateral formation so that an operator can easily put the device on the center of a ceiling glass piece. Figure 8 shows the vacuum suction device design.

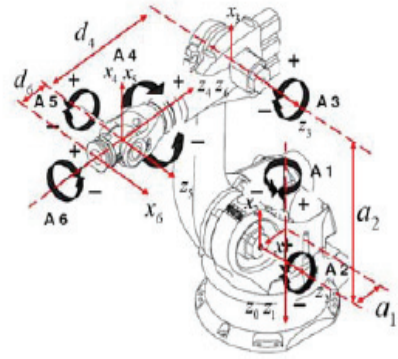


Figure 7 Simulations for Deck Design

Table 3 D-H table of the aerial lift

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$\pi/2$	a_1	0	θ_2
3	0	a_2	0	θ_3
4	$\pi/2$	0	$-d_4$	θ_4
5	$-\pi/2$	0	0	θ_5
6	$\pi/2$	0	$-d_6$	θ_5

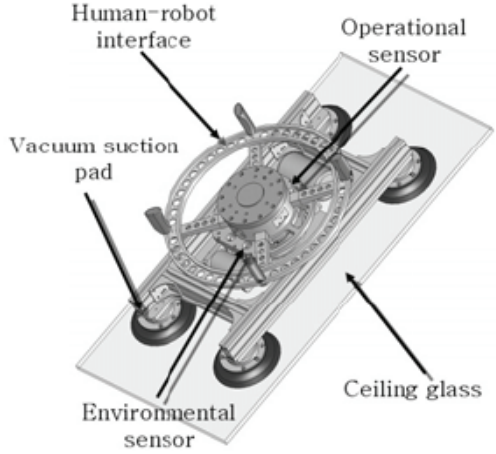


Figure 8 Vacuum Suction Device and the HRI Device

4.3 HRI Device

The HRI device is involved with installing ceiling glass by correlating the operator with a manipulator. This device plays a role in delivering the operator's intentions to the robot controller. It is positioned between the flange of the multi-DOF manipulator and the vacuum suction device, as shown in Fig. 8, while it is composed of two 6-axis force/torque sensors. When an operator supplies an external force containing an operational command on a handler of the HRI device, it is converted into a control signal to operate the manipulator with an operational sensor (6-axis force/torque sensor). If the manipulator comes into contact with a ceiling frame, the information about the contact force/torque is transmitted to the robot controller through an environmental sensor (6-axis force/torque sensor). It is important to note that an external force/torque transmitted through an environmental sensor or the operational sensor should occur separately from each other.

5. CONCLUSION AND FUTURE WORK

The ceiling glass installation robot presented in this study combines an aerial lift and a multi-DOF manipulator. One of the advantages of the proposed robot is the ceiling glass handling by human-robot cooperation. Included in this cooperation is the HRI device and the vacuum suction device combined with the multi-DOF manipulator. Development of the suggested robot does not end with the development of the robot system alone. A robotized working process including the suggested robot should be designed.

In this paper, a robot development method was introduced that complements existing systems. According to analysis of a target project, the functional needs were deduced for implementing the ceiling glass installation robot. A concept design was generated based on the functional requirements. The hardware design of the robot system is classified into three parts including an aerial lift, multi-DOF manipulator, and a HRI device.

After fabricating each part of the robot system, integration will be executed. Also, the control strategy and algorithm relating the human-robot cooperation, to which the hardware of the integrated system is to be applied, will be developed.

6. ACKNOWLEDGMENT

This work was supported by the SAMSUNG CORPORATION.

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THE DEVELOPMENT OF A GENERAL-PURPOSE AUTONOMOUS ROBOT

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ABSTRACT

This paper presents the ongoing research into the design and development of a general-purpose autonomous robot. The major components of the robot are four ultrasonic sensors, one electronic compass, three microprocessors, a laptop computer, and three motors for three wheels. Software architecture was developed to process the information obtained from the sensors, plan the motion of the robot, and send the commands to the motors. This allows the robot to operate independently of human control thus fulfilling the definition of an autonomous robot. A preliminary test was conducted in the field. The results indicate that the robot is capable of sensing static and dynamic obstacles in the environment and avoiding contact with them during motion.

KEYWORDS

Robot, Construction Automation, Autonomous Robot

1. INTRODUCTION

Automation and robotics have generated much interest in the construction community over the last two decades. The major reasons include high accident rates at construction sites, inconsistent product quality, and the amount of labor wasted in repetitive construction tasks, such as earthmoving or road inspections. Many researchers, such as Skibniewski and Russell [1] and Maynard et al. [2],

have developed robots for various construction applications. These robots are referred to as single-task robots; and, generally result in productivity and efficiency improvements.

One disadvantage of such single-task robots is their low cost effectiveness. Because the robots are designed for solving a specific problem in a pre-defined scenario, the researchers not only need to assemble the hardware (including sensors and actuators) for each application of the robot, but also need to develop algorithms to synchronize sensor inputs with the robot's motion. This usually involves a trial-and-error process and requires a large effort. Unfortunately, most of a robot's hardware and software architectures are incompatible with other robots, so the development efforts cannot be leveraged.

In this research we aim to develop an autonomous robot that has a flexible hardware and software architecture. An autonomous robot is an intelligent machine capable of performing tasks without explicit human involvement. The robot developed in this research will facilitate various research topics regarding construction automation in the future.

2. HARDWARE COMPONENTS

Since we aimed to develop a general-purpose robot, we designed hardware architecture with a high degree of flexibility and extensibility. It is composed of three modules: (1) a motion module; (2) a sensing module; and (3) a logic/control module (Figure 1). This architecture allows us to replace or add sensors and actuators in a way such that there is no detrimental influence from other parts.

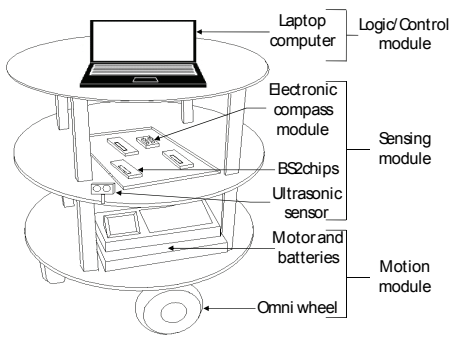


Figure 1 The Hardware Structure of the Developed Robot

The motion module is on the lowest shelf of robot. It includes two batteries, three omni wheels (wheels without lateral friction), a motor for each wheel, and power control devices (Figure 2). The sensing module is responsible for obtaining information from the external environment. All major components, excepting the ultrasonic sensors, are located on the middle shelf of the robot. It includes two BS2 microprocessors [3], one BS2p24 microprocessor [3], an electronic compass, and four ultrasonic sensors. The logic/control module is located on the top shelf of the robot. At present, we are using a laptop computer as the logic/control module. This module analyzes the information obtained from the sensors to make decisions on the robot's motions. Although the laptop computer satisfies our current needs, it could be replaced with one or several more powerful industrial computers; allowing for more complicated and advanced applications.

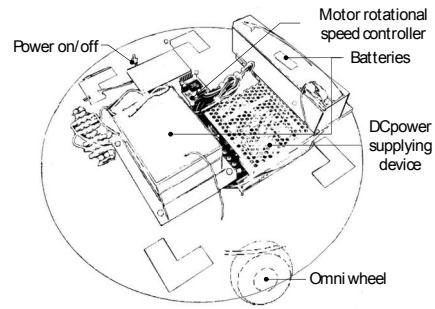


Figure 2 Motion Module

3. SOFTWARE COMPONENTS

To automate the robot, we developed software architecture to control and define the robot's behaviors. The software architecture enables the robot to process sensory inputs, perform cognitive functions and provide signals to output actuators. In other words, the software architecture of a robot defines how the job of generating actions from perceptions are organized [4]. This chapter first overviews the software architecture used in the robot, illustrates the information flow during robot's motion, and explains the implementation of the program to realize an autonomous robot.

3.1 Software Architecture

As shown in Figure 3, the software architecture is separated into three modules: the sensing module, the motion module, and the logic/control module.

The sensing module includes five sensory inputs: four inputs for ultrasonic sensors and one for the electronic compass. The information obtained from the sensors is transferred to the microprocessor in the logic/control module.

The motion module includes three motors, each of which controls a wheel. This module is designed to receive the information sent from logic/control module.

The function of the logic/control module is to integrate the information obtained from the sensors, execute cognitive functions, and then send the information to actuators, which in turn triggers the robot's motion. This module includes three microprocessors, a Bluetooth wireless communication chip, and a laptop computer. One of the microprocessors (BS2 chip) receives the data sent from sensing module. It integrates the data from all sensors and then sends it to the central microprocessor (BS2p24 shown in Figure 3). Since the BS2p24 microprocessor has greater computation performance than the other microprocessors, it performs the function of central communicator between the sensors, the computer and the motors. A Bluetooth chip is employed to wirelessly link the BS2p24 microprocessor with the computer. The BS2p24 microprocessor also needs to send commands to the BS2 microprocessor, which coordinates the three motors.

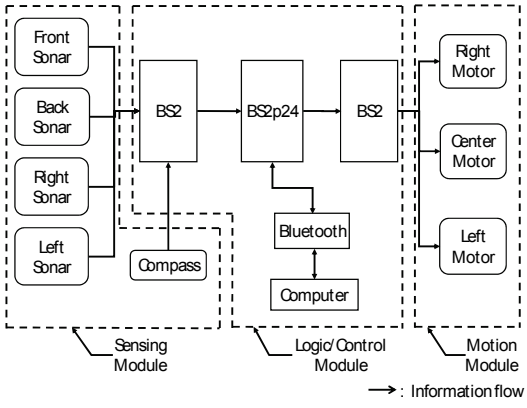


Figure 3 Software Architect of the Robot

3.2 Controller Interface

Controlling the motion of the robot requires simultaneously controlling the three wheels, which would be extremely complex for users. Therefore, a user interface that simplifies the control and allows users to control the robot's motion using a computer input device was developed. We used Microsoft Robotics Studio [5] as a development platform. Figure 4 shows the control interface.

Our major effort in this part of robot was linking the computer interface with the BS2p24 microprocessor via Bluetooth wireless protocol (shown in Figure 3). A web service (a piece of software that makes itself executable over the Internet) is constantly connected to the BS2p24 microprocessor. By connecting with the web service, we are able to use a trackball, as shown in the control interface, to control the robot. For example, we may define that when the user rolls the trackball upward, the intention is to move the robot forward. To achieve the goal, we wrote a computer program to send the commands to the BS2p24 microprocessor. The program interprets these commands to control the speeds of each of the three wheels. The combined of effect of the rotational motion of the three wheels, in combination, drives the robot forward. Similarly, we also define: (1) that rolling the trackball to the right is to turn the robot to the right (rotate clockwise from the top view); (2) that rolling the trackball left is to turn the robot left (rotate counter-clockwise from the top view); and, (3) rolling the trackball downward is to move the robot backwards.

This interface also displays the status of the robot, such as its position and orientation. It also displays any information received from the sensors. In Figure 4, we can see the obstacle detected by laser scanner result in the sub-window shown in obstacle display (right bottom of the window).

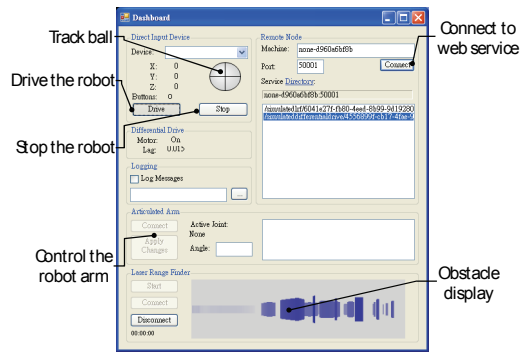


Figure 4 The Robot Control Interface

3.3 Motion Control

Because we are developing a general-purpose robot, we need to control not only the movement of the robot but also rotation of the robot. Thus the robot can be moved to a target position and target orientation. To achieve the goal, we define two wheels as the front wheels. The intersection between the center of the robot and the imagined extension lines of the front wheels was defined as the forward direction. The third wheel functions as a rudder, for rotation.

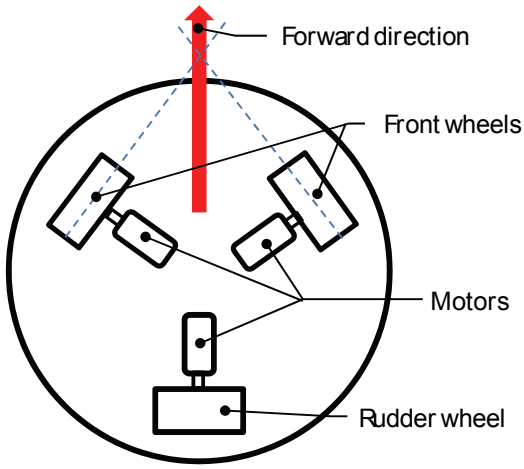


Figure 5 The Wheels and Forward Direction

After defining the forward direction, let's discuss how the robot moves forward, backward, turns right and turns left; all by controlling the wheels. When the robot moves forward, the motor for the left front wheel rotates counterclockwise and the motor for the right front wheel rotates clockwise with equal angular speed (vectors shown in Figure 6 (a)). When the robot moves backwards, the motor for the left front wheel rotates clockwise and the motor for the right front wheel rotates counterclockwise (vectors shown in Figure 6 (b)). Because the omni wheel is frictionless during lateral movements, the rudder wheel remains still during both forward and backward movement. When the robot turns right, the motors for all three wheels simultaneously rotate clockwise with equal angular speed (as shown in Figure 6 (c)). When the robot turns right, the motors for all three wheels simultaneously rotate counterclockwise with equal angular speed (as shown in Figure 6 (d)). If we would like to control the robot arbitrarily, we interpolate the rotational speeds found in the two of the four cases to compute the appropriate angular speeds for each of the three motors.

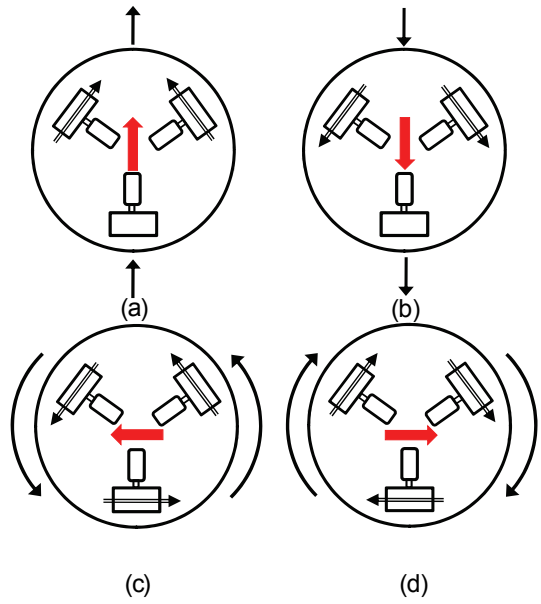


Figure 6 Wheel Controls: (a) Move Forward; (b) Move Backward; (c) Turn Left; (d) Turn Right

4. FIELD TEST

We conducted a field test to verify the integration between the hardware and software. We also wanted to see whether this robot fulfills the definition of an autonomous robot – a robot capable of intelligent behaviors without human controls. During the test, we wrote a computer program and installed it on the computer located on the top shelf of the robot. This computer controls the behavior of the robot and enables it to travel smoothly in an indoor environment.

Two major behaviors are coded for in the computer program. One is random patrol (walk behavior) and the other is obstacle avoidance. The random walk behavior can be achieved by assigning a random distance for the robot to move forward and a random angle for it to rotate. By repeating the forward and rotational motions, the robot will patrol randomly in the environment. Obstacle avoidance is achieved by analyzing the information obtained from sensors coupled to the motion controls.

To seamlessly shift between the two behaviors, Concurrency and Coordination Runtime (CCR) [5]

was employed. CCR is the mechanism provided by Microsoft Robotic Studio. It allows programmers to define multiple executing threads with different priorities. It also provides "dispatcher", a mechanism which executes the viable thread with a higher priority. By controlling the priority of each thread, users are able to integrate multiple behaviors in the robot. To integrate the random patrol and obstacle avoidance behaviors, we set obstacle avoidance behavior as having the higher priority. When the sensors detect an obstacle, the obstacle avoidance behavior is activated. Since the sensors are at different locations in the robot, various different obstacle avoidance behaviors are defined.

Figure 7 illustrates one of the robot's behaviors in the test. We placed the robot in a hallway of the civil engineering building at National Taiwan University. A tester was assigned as a dynamic obstacle. During the test, the robot first patrolled randomly in the environment (Figure 8 (a)). While it was close to the dynamic obstacle, the tester, the front ultrasonic sensor received an ultrasound response (Figure 7 (b)). Then the robot moved a random distance backwards. Finally it rotated by a random angle (Figures 7 (c) and (d)). When the obstacle could not be detected by any of the sensors, the robot disabled its obstacle avoidance behavior and returned to random patrol behavior.

5. CONCLUSION

In this research, we have built an autonomous robot. The robot's electronic hardware consists of five sensors, three motors, three microprocessors, and a laptop computer. The hardware is separated into three shelves, a motion/sensing module, a control module and a logic module. We provided software architecture that integrates the information flow in the robot. We also developed a user interface to allow users to control the robot with high level commands and at the same time display the information collected by the sensors on the robot. From the results of the preliminary field test, we determined that the robot is capable of performing a random patrol in an unfamiliar environment; and, collision with both static and dynamic obstacles can be avoided.

In the future, we plan to integrate a laser range finder and camera into the robot. We also plan to use the robot for various pavement inspections, such as measuring pavement roughness.

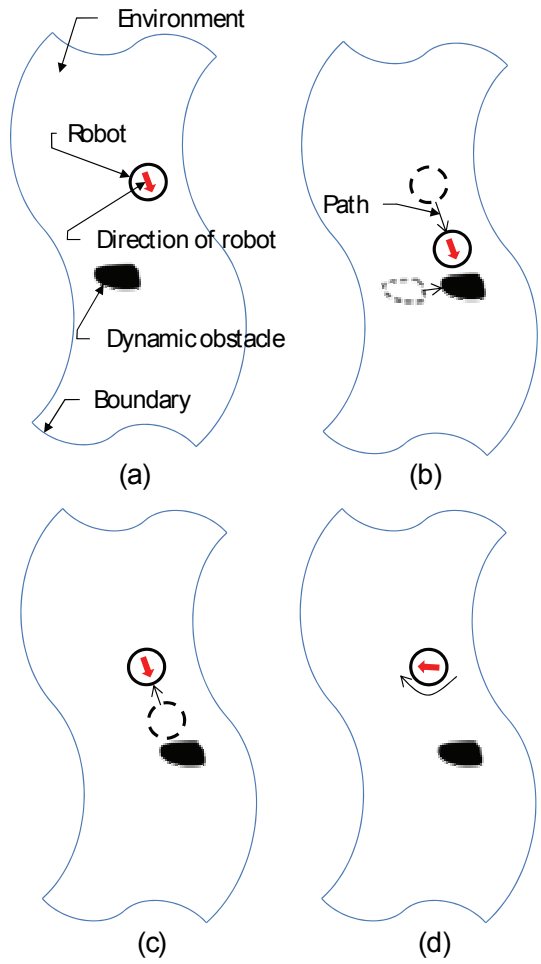


Figure 7 Tests for Autonomous Robot: (a) Random Patrol; (b) Sensing Obstacle; (c) Obstacle Avoidance; (d) Finding Alternatives

6. ACKNOWLEDGMENT

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INTUITIVE OCU (Operator Control Unit) OF MFR (Multipurpose Field Robot) ON CONSTRUCTION SITE

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ABSTRACT

Recently, there has been a lot of interest concerning remote-control construction robot manipulation in hazardous operation environments including construction sites. However, there are problems involving the method of remote-control in unstructured work environments such as construction sites. In this study, an improved MFR system is described, which helps a human operator to easily install construction materials through an intuitive Operator Control Unit (OCU) on construction sites. The OCU consists of a force reflecting joystick and a vision system. The active compliance control and bilateral communication for strategic control is also described. In order to evaluate the proposed OCU, the installation of construction materials is simulated.

KEYWORDS

Intuitive, OCU (Operator Control Unit), Construction Site

1. INTRODUCTION

Recent research has found that a lack of skilled manpower in the construction industry is rapidly becoming a serious problem. One of the solutions suggested to solve these problems is robotization or automatic installation [1]. Since the late 1980s, construction robots have helped operators perform hazardous, tedious, and health-endangering tasks in heavy material handling. Isao et al. discussed the appropriateness of the automation technology for installation of a curtain wall [2]. Masatoshi et al. proposed the automated building interior finishing system and a suitable structural work method is described [3]. Lee et al. developed an automation system (ASCI; Automation System for Curtain Wall Installation) that is suitable for mechanized construction, which enables simpler and more precise installation than existing construction methods, while improving safety during installation [4].

Robots can be classified into two groups: those that can carry out work and coexist with humans in atypical environments unlike production factories, and those that do repeated work according to a standard program such as part assembly, or welding and coating in the automobile or electronics industries. In this discussion, a field robot is defined as one that executes orders while moving around in a dynamic environment where structures, operators, and equipment are constantly changing [5,6]. Until now, the development process of field robots has focused on the single-task robots, separate from planning to designing, production, testing, and inspection. This separation

leads to the inefficient use of time and resources as well as to limited utility. In order to solve this problem, a Multipurpose Field Robot (MFR) is suggested, as shown in Figure 1 [7].

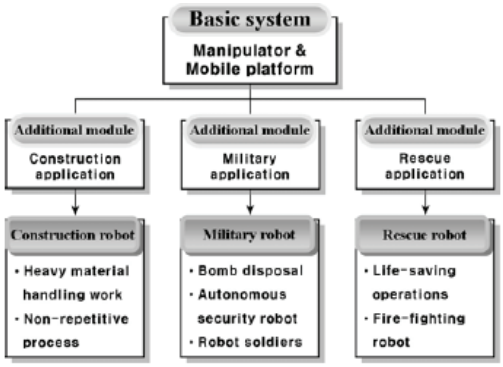


Figure 1 Framework of MFR

Construction robots are defined as field robots that execute orders while operating in a dynamic environment where structures, operators, and equipment are constantly changing. Therefore, a guidance or remote-controlled system is the natural way to implement construction robot manipulators [8, 9]. However, remote-controlled systems have to overcome some problems. For example, it is difficult to cope with malfunctions immediately when unexpected situations occur during construction work. In addition, it is difficult to gain environmental information for suitable operator commands.

In this paper, the intuitive Operator Control Unit (OCU) is introduced in order to solve these sorts of problems when the remote-controlled MFR is operated. The intuitive OCU consists of a force reflecting joystick and a monitoring device, which grasps the situation around the MFR. The control strategies are bilateral communication and active compliance control for smooth interaction between a human and a robot. Recently, an experiment related to installing the construction materials was executed by applying the proposed intuitive OCU to the MFR system.

2. MFR SYSTEM PROBLEMS

The MFR system was developed by Lee et al.[7] for installing heavy construction materials. The MFR system combines a basic system with an additional module for construction. Considering the workspace and mobility, a 6DOF manipulator and a 3DOF mobile platform were suggested for use in the basic system. Moreover, it is possible to change the elements of the basic system according to load specifications. An additional module, which is used for construction work along with various devices, is suggested to incorporate the MFR in construction work. It consists of hardware (HRI: Human-Robot Interface) and software (HRC control: Human- Robot Cooperative control). This system was used in experiments for installing construction material. Figure 2 shows the MFR system that consists of the basic system and the additional module for construction work.

Figure 3 shows a simulation of the installation of construction materials with the proposed MFR system. The operator manipulates the HRI device near the MFR. A serious accident may occur when an unexpected situation occurs during installation operation.

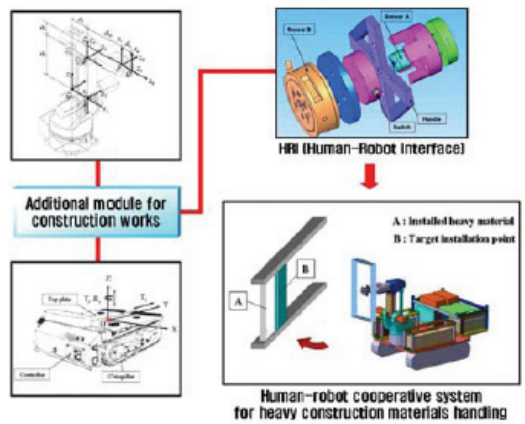


Figure 2 MFR System for Construction Work



Figure 3 Simulation of Installing Construction Materials

In this study, the upgraded additional module is introduced: the intuitive OCU for a remote-controlled MFR system.

3. UPGRADED ADDITIONAL MODULE: INTUITIVE OCU

3.1 Hardware

The hardware of the upgraded additional module is partitioned into an intuitive OCU, an end-effector, a CCD camera. A 6DOF manipulator and a 3DOF mobile platform are controlled by the intuitive OCU. The construction robot control makes use of a remote-controlled system. This control method is important because the operator does not get accurate information about work and situations, in order to respond instantly during changing work environments in real time. To address these problems, the concept of a force-reflecting joystick and a vision system is introduced, which transmit work information to the operator. The operator controls the manipulator using the joystick of the intuitive OCU, as shown in Figure 4, to perform theinstallation. There are 8 channels for work performance on the force-reflecting joystick and a lever rotates to the front, back, left, and right sides. It consists of a lever installed gear box, a motor to execute the force-reflection, a potentiometer to measure the rotating angle of the lever, and a control circuit device.

Figure 5 shows the F/T sensor for measuring contact force. If the construction material contacts to the environment (experiment system), information concerning the contact force is transmitted to the reflecting joystick through a wireless module. A motor rotates according to the signal of the transmitted information that is transmitted to the installed control circuit device at the lever in the force-reflecting joystick. Therefore, the operator will know the contact situation of a construction material through the reaction force by the rotating lever. The construction material can be installed safely by grasping the work situation of the robot through a CCD camera on the manipulator.

The end-effector of a construction robot varies according to the properties of the construction materials. Since this paper aims at installing construction materials with relatively smooth surfaces, a vacuum suction device is used as the end-effector. If the vacuum suction device that is located between the HRI device and the construction material makes a vacuum contact with the use of a motor, the construction material and end-effector are strongly attached to each other. Additional safety devices for the operator and an alarm device for alerting neighboring operators of the robot operation are necessary, while considering environmental conditions and characteristics of construction sites. Also necessary are control devices and interfaces that implement software and the separate power supply systems to operate the robot.

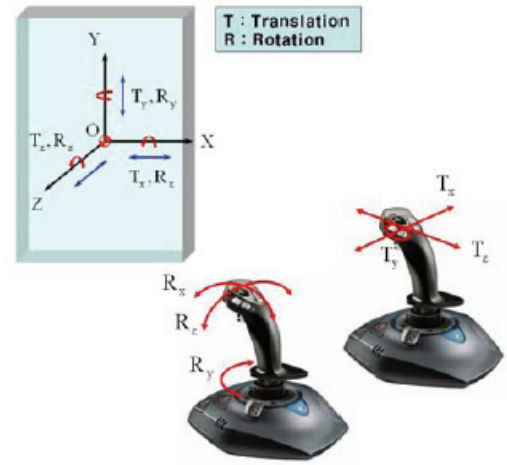


Figure 4 Force-Reflection Joystick (Logitech Co.)

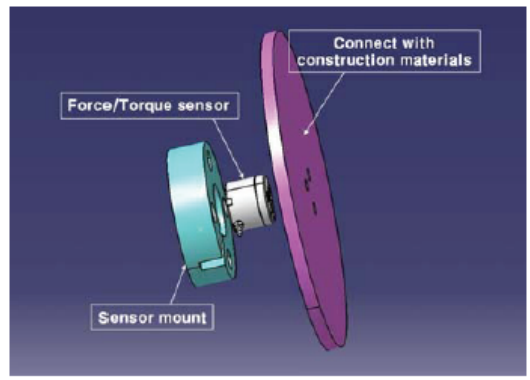


Figure 5 F/T Sensor for Measuring Contact Force

3.2 Software

The software of the upgraded additional module refers to a control algorithm which is necessary for installing construction material with the intuitive OCU. In this paper, ‘free space motion control’ and ‘constrained motion control’ are proposed as

methods to control a MFR with the intuitive OCU. The free motion control is used to carry construction materials to a desired position. The constrained motion control is used to install construction materials and precisely move them when the end-effector of the manipulator contacts the environment. Bilateral communication and an active compliance control are proposed for the constrained motion control. Bilateral communication can occur for two situations simultaneously. Initially, the operator transmits command signals to the force reflecting joystick. Then, the input signals have cartesian-space coordinate system attributes. These are different attributes than the joint-space coordinate system for the driving actuators of the manipulator. Simultaneously, reaction forces are transmitted to the operator when the end-effector of the manipulator contacts the environment. Figure 6 shows the flowchart for the bilateral communication. The active compliance control algorithm is executed based on the operator's commands (forces), which are input by the force-reflecting joystick of the intuitive OCU, and information on the reaction forces obtained by the manipulator of the MFR when it contacts the environment. It can protect the MFR system and the construction material by regulating the system compliance when contact with the environment occurs. If the reaction forces exceed the elastic limit of the construction material, then a manipulator moves the position, which reduces the reaction forces. At the same time, the operator is able to intuitively control through the reaction forces when the manipulator of the MFR makes contact with the environment at a long distance. Figure 7 and Table 1 show the signal flow of the control system.

4. EXPERIMENT

An experiment for installing construction material was implemented, in order to evaluate the performance of the proposed intuitive OCU. Initially, construction material on the ground is gripped to the MFR with a vacuum suction device, and the MFR is moved to an installation position by command signal of the intuitive OCU. The operator can handle the construction materials through a CCD camera that is attached to the body of the manipulator as shown in Figure 8. The construction material carried to the vicinity of an installation position is installed through interaction with experiment system. That is, compliance occurs upon contact, so that the press pit for the construction material and the MFR system is completed safely. Furthermore, at this time, the reaction force is transmitted to the operator and it provides an effective operator command. In this experiment, the weight of construction material was limited to 60[N], which considers the specifications of the manipulator and the manufactured models of a curtain wall that is a type of huge construction material.

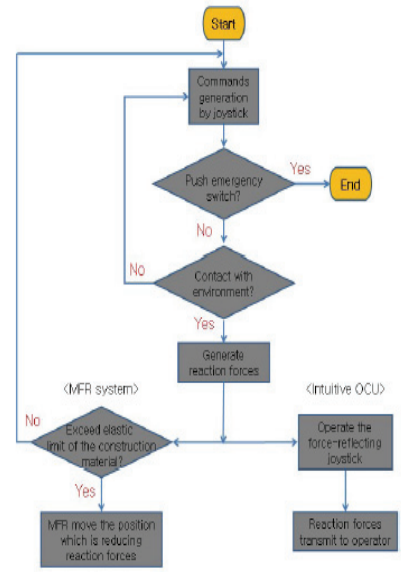


Figure 6 Flowchart for Bilateral Communication

Table 1 Signal Description of Figure 7

Signals	Description
A	Command signals (cartesian-coordinate system)
B	Digital signals
C,H	Wireless signals
D	Control signals (current)
E	Contact forces
F	Reaction forces
G	Sensor signals (analog signals)
I	Reaction force signals
J	Control signals (current)
K	Reaction forces

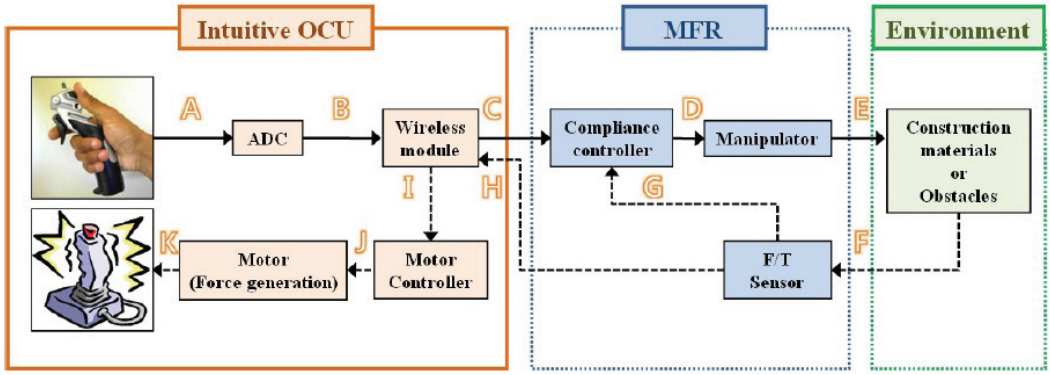


Figure 7 Signal Flow of Control System

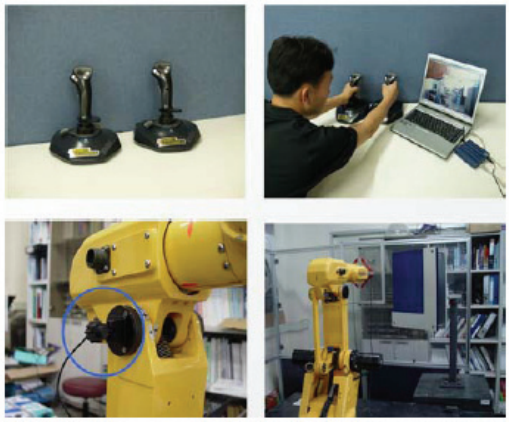


Figure 8 Experiment System

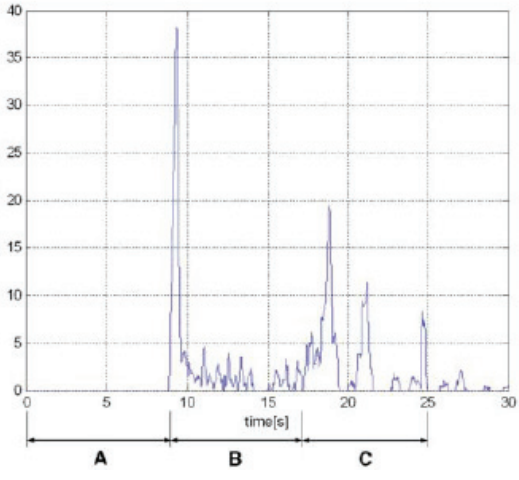


Figure 9 Experiment Result (Contact Force)

$$F(\text{contact force}) = \int_0^T \frac{\sqrt{F_x^{\,2} + F_y^{\,2} + F_z^{\,2}}}{T(\text{time})} dt$$

Figure 9 shows the contact force from the simulation for installing construction material using an experimental system. A section from 1 second to 8 seconds is a free-space motion, in which the construction material is carried to the installation position. A section from 'A' to 'B' is a step to control the compliance when contact with the environment occurs. After 17 seconds, a construction material controlling the compliance is carried horizontally and vertically to be inserted between the supporting board. This signal is transmitted to the motor controller in the intuitive OCU through the wireless module.

5. CONCLUSION

The proposed intuitive OCU combines force reflection with a vision system. An operator receives transmitted reaction forces from a force reflecting joystick with bilateral communication. The active compliance control algorithm is executed that is based on an operator's commands (forces), which are input by the force-reflecting joystick of the intuitive OCU and information on the reaction forces obtained by the manipulator of the MFR when it contacts the environment. It can protect the MFR system and the construction material by regulating of system compliance when contact with the environment occurs. This algorithm is verified by the results of the experiment for installing the construction material.

The intuitive OCU is expected to conduct safer and more accurate work at construction sites as well as hazardous environments that a human will not likely approach. In the near future, an autonomous MFR system will be developed that can avoid obstacles and generate a path automatically when moving from point-to-point in construction sites.

6. ACKNOWLEDGMENT

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CONSTRUCTIONS MOBILE ROBOT AND WORKING TECHNOLOGY

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ABSTRACT

In this paper is presented a mobile robot for the buildings construction, which, endowed with gripping and adequate tools, can carry out operations of handling, masonry or finishing in the construction industries.

The robot has in its componence the following mechanisms:
- mechanism of orientation with 2 DOF's (2 R);
- mechanism of positioning with 3 DOF's (2 TR);
- mechanism of displacement with 1 DOF's (R);
- steering mechanism with 1 DOF (T).

A mechanism of orientation by horizontal locus is added and ensures, before beginning work in a given position, orientation of the robot's platform in horizontal position. The orientation is made using 4 devices to fix with mechanical action, which have also the role to support the robot during work. The orientation is not made in a robotized mode, but in an automated mode, using an inclinometer to measure the slope according to two axes.

KEYWORDS

Mobile Robots, Civil Engineering Flexible Cell

1. INTRODUCTION

The mobile robot for construction was designed to complete different technological tasks in construction works like: masonry and finishings, making it the central component of a robotized flexible cell for construction of residential buildings of 1...3 floors.

The mobile robot for construction is represented in figure 1 and is composed of an orientation mechanism with 2 DOF's RR (axes I and II), a positioning mechanism with 3DOF's TTR (axes III, IV and V) and chassis with mechanisms for moving, steering and wedging.

2. ORIENTATION MECHANISM

The orientation mechanism of the mobile robot for construction is composed of a driving mechanism for axis I, fig.1, pos 1, and driving mechanism for axis II, fig.1 pos 2.

The driving mechanism of axis I, is presented in figure 2 and is composed of: motor 1, bracket 2, planetary reducer with pins 3, flange 4, which connects the reducer with output shaft 5.

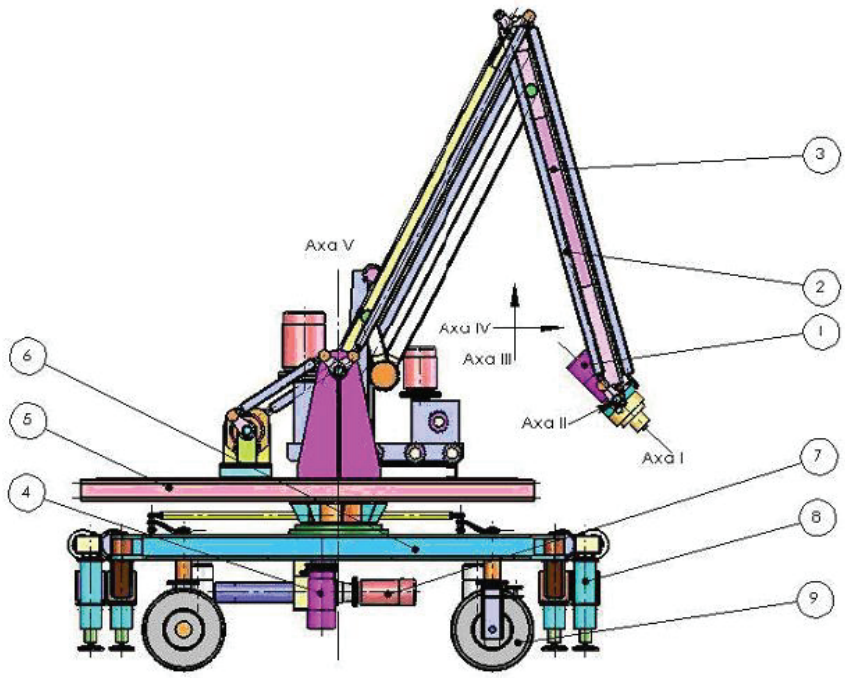


Figure 1 Mobile Robot for Construction

Output shaft 5 is retained by ball bearing 6. On output shaft 5 is fixed the grasping device which rotates around axis I together with the output shaft. The motor is provided with brake and an encoder.

The driving mechanism of axis II is presented in figure 3 and is composed of two mechanisms with bars placed on one side and the other of the arms of the positioning mechanism and a motion mechanism. The two mechanisms with bars are each composed of three parallelogram mechanisms. Following notations from the figure, the mechanism with bars from the right side of the positioning mechanism is composed of the parallelogram mechanism 3, 4, 5, platform, parallelogram mechanism 6, 7, 8, inferior arm of the positioning mechanism and 9, 10, 11, superior arm of the positioning mechanism. The mechanism from the left side is identical but the crank is rotated 90^0 in vertical plane, relatively to the crank from the right side. By locating the cranks this way, is allowed the continuity of the movement taking each other out from blocking positions.

The motion mechanism is composed of motor 1 and planetary reducer with pins 2 having the output shaft with two exits. The output shaft of the reducer is joined with the two driving cranks of parallelogram mechanisms from left and right. The shaft 12 materializes the axis II and is fixed to the cranks and the bracket of the driving mechanism, axis I, 14. The shaft is supported by ball bearings 13 fixed to the superior arm of the positioning mechanism.

How it works – The output shaft from the reducer rotates the cranks 3 which are move the three parallelogram mechanisms. All the cranks of the parallelogram mechanisms rotate synchronously with the crank 3 (reduction ratio 1:1). The crank 11 rotates around axis II the shaft 12 which rotates relatively to the axis II the bracket and mechanism 14. The motor is provided with brake and an encoder. By stopping the motor, the mechanism 14 is locked in the desired position. Parallelogram mechanisms have the duty to maintain the mechanism 14 in this position independently of the positioning mechanism movements. To both mechanisms, the feed-back is closed to the motor output shaft and this is the reason that the mechanical transmission has to be backlash free. This requirement asked for the planetary reducers with pins.

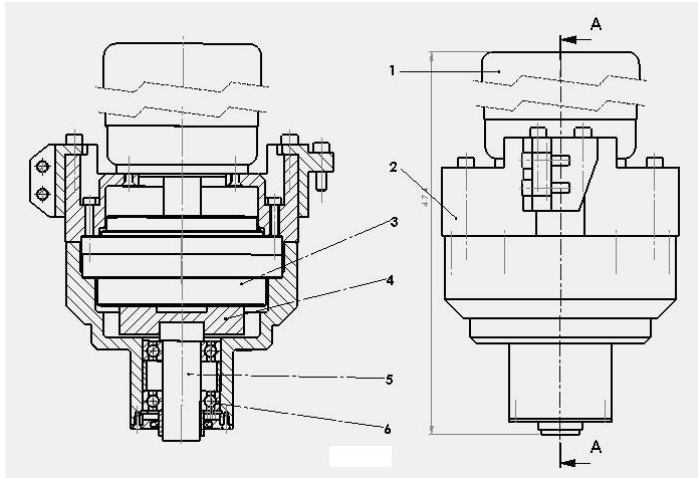


Figure 2 Driving Mechanism of Axis I

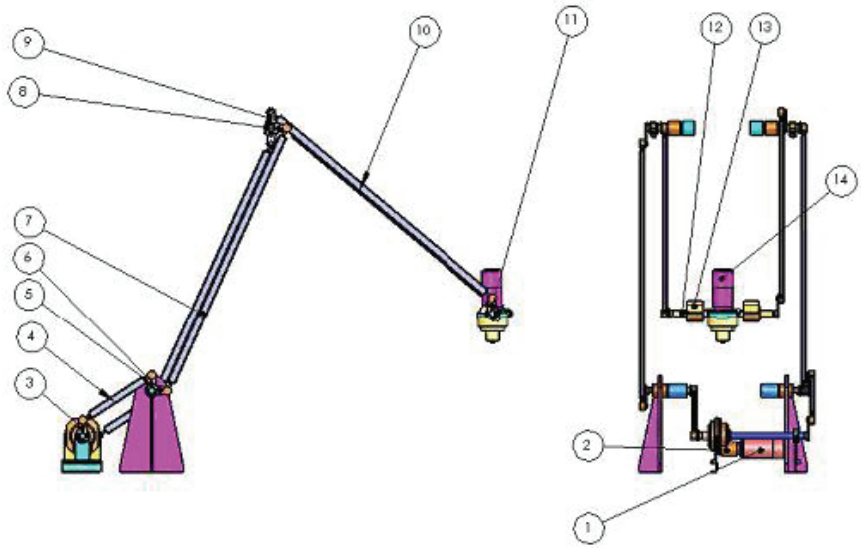


Figure 3 Driving Mechanism of Axis II

3. POSITIONING MECHANISM

The purpose of the positioning mechanism (Fig. 1 pos. 3) is to move the orientation mechanism and the grasping device in different points of the workspace. It is composed of (fig. 4), a bar mechanism, which makes the movements by axes III and IV and the rotation mechanism around the axis V.

The bars mechanism is composed of a pantograph mechanism and a mechanism for moving vertically and horizontally the joint C, (pos. 5). The pantograph mechanism is composed of the superior arm (pos.1), inferior arm (pos.4) and bars 2 and 3 fixed through a joint in C and to bar 2 respectively 3 making this way a parallelogram mechanism. The mechanism is attached to the fixed joint A in platform 6 ant through C to the motion mechanism 5.

How it works – by moving the joint C parallel to the axes III or IV is obtained an amplified movement with the characteristic coefficient K of the mechanism to the joint G of the orientation mechanism by axis III respectively IV.

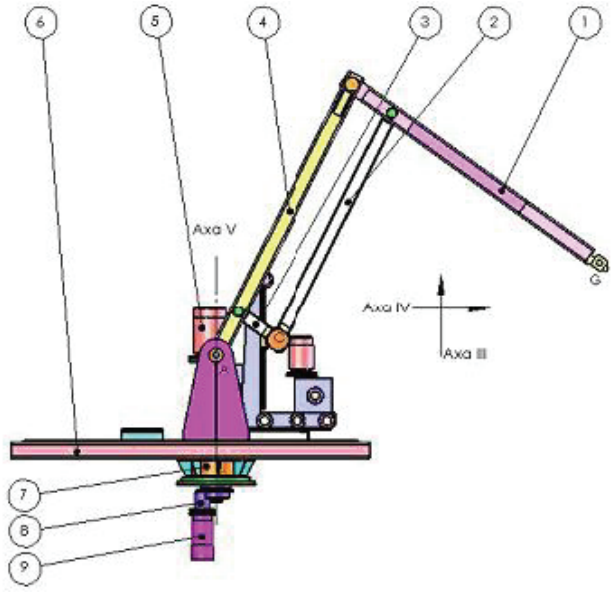


Figure 4 The Positioning Mechanism

By moving simultaneously joint C by the two axes, curves of second order in the pantograph's mechanism plane. By rotating simultaneously the platform, are obtained spatial trajectories for the joint G are obtained.

Rotation mechanism relatively to axis V is composed of motor 9, planetary reducer with pins 8 and axial ball bearing in case 7. The motor is provided with brake and an encoder. In this case the feedback is closed at motor shaft and reason to which it was used the planetary reducer with pins (very small backlash, considered negligible).

4. CHASSIS CONTAINING MECHANISMS FOR MOTION, STEERING AND WEDGING

4.1 Chassis and Wedges

Are represented in figure 5 (closed position of wedges) and figure 6 (opened wedges). The four wedges (pos. 2) are articulated to the chassis corners 1. Wedge opening is done manually by rotating them at the working site. Wedging is done automatically by the computer by raising or lowering the chassis.

Every wedge is composed of a folding arm 3, case of the wedge 6, telescopic boom 7 and the shoe 8. Raising and lowering are done by using the worm gear motors 4 and 5 which drive a screw mechanism.

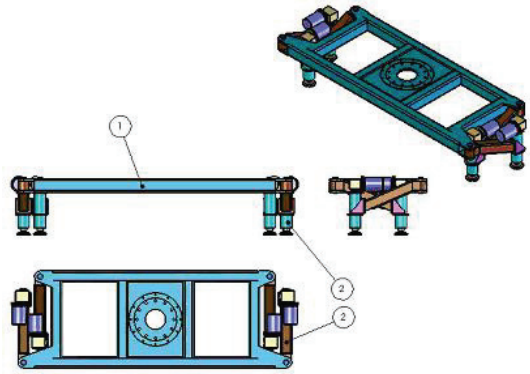


Figure 5 Chassis with Closed Wedges

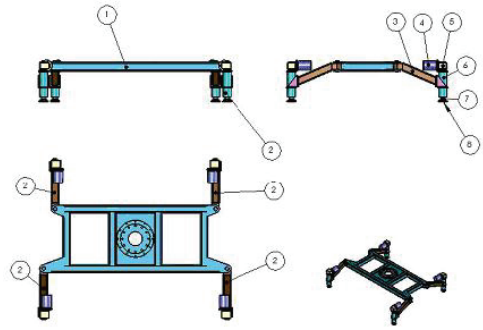


Figure 6 Chassis with Opened Wedges

4.2. Steering Mechanism

This is a parallelogram mechanism and is presented in figure 7. This mechanism insures the rotation of all the four wheels with an angle of 0÷90° allowing the robot to move on different directions, with zero turn radius.

If the chassis need to rotate around the vertical axis V, in order to be placed for an desired direction, for example parallel to a wall, the wheels are rotated 45° in horizontal plane and by moving the driving wheels in opposite way a rotation of the chassis in horizontal plane is obtained.

The steering mechanism is composed of the driving mechanism, and the bars mechanism. The driving mechanism is composed of the motor with brake and encoder, the planetary reducer with pins 3 and ball-screw mechanism 4. The wheels are articulated to the low part of the brackets F The vertical shafts of the brackets are articulated to the chassis through ball bearings 1 and are fixed to.

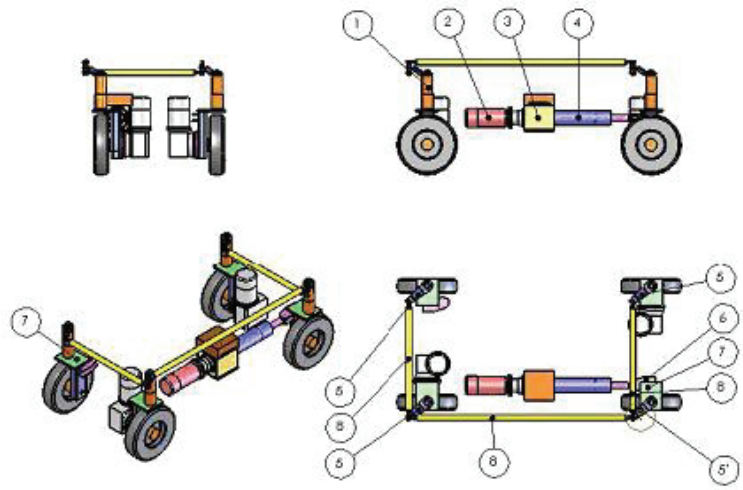


Figure 7 Steering Mechanism

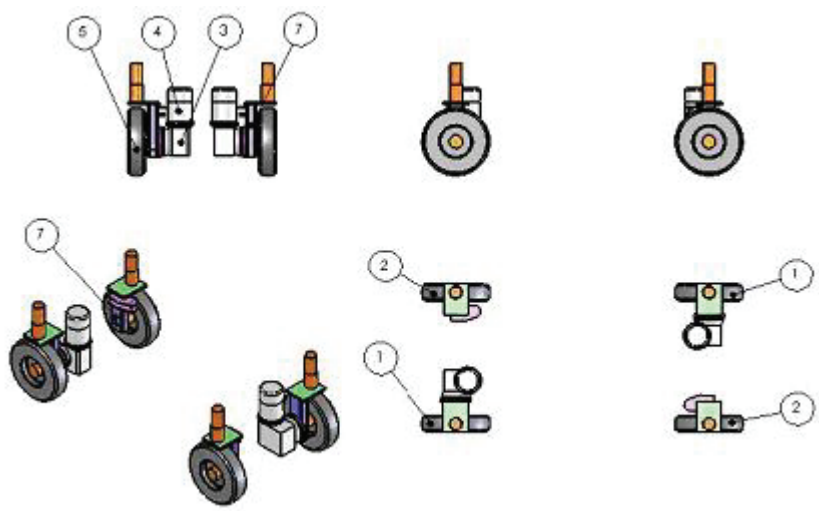


Figure 8 Motion Mechanism

the cranks 5 of the 3 parallelogram mechanisms (1, 5, 8, 5'). Rotating the crank 5' with the desired angle, the movement is transmitted to the other cranks which rotate with the same angle. The crank 5' is rotated by the driving mechanism which is articulated to the frame 7 and fixed to the crank.

4.3. Motion Mechanism

Motion mechanism is presented in figure 8. Motion mechanism is composed of 4 wheels articulated to the frames 7 with two driving wheels 1, and two are free 2. The driving wheel 5 is powered by a worm gear motor 3, 4.

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INFORMATION AND COMMUNICATION TECHNOLOGY

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AUTOMATION OF SCHEME PREPARATION AND BOQ CALCULATION FOR L&T-ALUFORM

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ABSTRACT

Aluminium Formwork System is a comparatively new technology in India. Generally, aluminium formwork consists of standard sized panels and custom sized panels. The total area of custom shaped formwork elements can be reduced by optimizing the allocation of standard-sized formwork elements. This can in turn lead to large savings in formwork costs and time for scheme preparations. An application to automate the optimization and scheme preparation for L&T Aluminium Formwork was developed using Visual Basic 6.0. The application captures spatial details of a building element from an AutoCAD Drawing and uses an optimization algorithm to develop a formwork scheme as well as a Bill of Quantities. The application also takes into account the formwork elements available at site and optimizes their usage. The tool has been validated with four cases taken from two ongoing projects. The validation shows improvement in usage of standard sized formwork elements in the order of 10% to 13% for complex shapes and 1% to 2% for simple shapes.

KEYWORDS

Scheme Preparation, Aluminium Formwork, Bill of Quantities, Optimization

1. GENERAL

Formwork systems are the backbone of construction activity especially for high-rise buildings. According to the System Formwork Manual of L&T ECCD, formwork systems constitute about 40% of the cost and 60% of the time for any construction activity.

Amongst the various alternatives currently available for mass housing construction, aluminium formwork not only satisfies the main criteria of speed, quality and economy, but also has other attributes such as safety, lightness of weight, fewer number of components, etc. This system has been in use in India for nearly a decade and has proved its worth on a number of recently constructed jobs.

Details of each and every formwork element are essential to build the formwork for any structure. These details are represented in a drawing known

as the "Scheme Drawing". Thus far the scheme drawings for L&T aluminium formwork – a category of Aluminium formwork patented by Larsen & Toubro ECC Ltd - are mostly prepared manually. Generally, the formwork engineer works out the layout of formwork elements for a particular structure. Based on the formwork engineer's suggestions, the draftsman prepares the scheme drawing in AutoCAD and list outs the bill of quantities of the formwork elements used for that structure.

Aluminum formwork elements can be divided into two groups, one being standard size/shape elements and the other, custom size/shape elements. Generally, for any structure, formwork has both standard size/shape elements and custom size/shape elements. Standard-sized formwork elements are generally readily available, but the custom sized, shaped formwork elements have to be fabricated by order. One has to work out the shape and total number of the custom-sized panels required from the drawings well before the execution of the work. The special fabrication of custom-sized panels, their incorporation in the drawings and the preparation of a Bill of Quantities consume a lot of time and resources and increases cost.

Therefore it would be beneficial to reduce the total area of custom shaped formwork elements by allocating the standard-sized formwork elements in a systematic manner using the available software and optimization techniques. Manual planning methods are far less likely to yield optimal formwork schemes.

2. LITERATURE REVIEW

A number of researchers and investigators have studied the impact of various kinds of formwork systems and resources on critical matters such as project duration, project cost, productivity achieved, etc. Also a lot of work has been done related to the optimum utilization of space in setting up of site facilities - storage yards, labour colony, plants and major equipment like batching plant, tower cranes, concrete pumps etc. Studies have been made comparing the effectiveness and efficiencies of various formwork systems.

2.1. Review of the Academic Literature on I.T. Applications for Formwork

While disciplines such as structural analysis are reaping the benefits of computer implementation; temporary works design lags well behind. Some of the reasons given by temporary works designers are that their designs are very practical and depend largely on the designer's experience and engineering judgement (Taha and Price, 1991).

A package developed by Taha and Price (1991) produces design details, a schedule of quantities, a cost comparison between purchased and hired proprietary formwork, and a cost estimate.

A conceptual model for implementing the stiffness method in formwork design was also proposed by Taha and Price (1997). They assessed the use of existing software for solving the stiffness equations. This is used to develop the detailed formwork design program.

Huang, Chen and Sun (2004) employed computer process simulation techniques in their research for the study of different form reuse schemes to use gang forming systems in building construction.

Many researchers are developing IT applications for the use of formwork. At present, the research and development of IT applications for formwork are limited to a few areas of formwork such as the design of formwork, cost estimation, cost comparisons between different formwork systems and formwork labour productivity measurement tools [2]. Aluminium formwork is a comparatively new formwork system, and has not been the subject of automation research. In addition automation of formwork scheme preparation – the area of research that we plan to pursue – has not been adequately addressed in the existing research on IT applications for formwork systems.

2.2. A Review of Tools Used in Practice

DOKA has developed a software called "Tipos-DOKA Formwork Planning 5.0" for planning and design of Doka-formwork. Tipos is a planning and organization tool that helps to deal with a wide range of different tasks in connection with the planning and management of formwork [6].

PASCHAL has developed a software called "PASCHAL- PLAN light" for automated

formwork design. The programme automatically creates a formwork design for given layout. By means of the default values the user can modify the formwork drawing according to his needs [7].

Despite the existence of these tools, there is little or no work done currently regarding the automation of scheme preparation for A*luminium formwork*. Automating the scheme preparation and preparing the bill of quantities will definitely improve the labour and material productivity and efficiency of aluminium formwork systems.

3. SCOPE OF THE PROJECT

A Literature survey was done in the area of formwork, to discover the major areas of research and to discover gaps in current knowledge. From this survey, it was found that automated preparation of scheme drawings for an aluminium formwork (L&T- AluForm) had not been dealt with earlier in the academic literature. Therefore this is picked as the area of research. The scheme drawings are preparing manually for L&T-AluForm. We first needed to analyse the current manual practices of scheme preparation and to develop the generalised methodology for scheme preparation of aluminium formwork. We then built up flowcharts/algorithms for the generalized methodologies. Finally we developed a software tool, by using Visual Basic 6.0, with reference to the above flow charts, to automate the process of scheme preparation for L&T – AluForm, for:

- Scheme Preparation for Slabs / Floors and
- Calculation of Bill of Quantities

The outputs of the software tool are:

- An optimised formwork scheme based on the available resources in the inventory (or for the case of unlimited resources)

4. SOFTWARE PLATFORM SELECTION

Generally, structural drawings are prepared in the CAD environment. Therefore the development environment must be able to interact with AutoCAD, to read/write to the AutoCAD drawings. The developing environment must also interact with MS Excel to read and write the bill of the quantities for the formwork. (Most of the construction engineers in India use MS Excel to store their data)

Potential software development environments were, C, C++, C#, Visual C++, Visual Basic, Auto LISP, Visual LISP, FORTRAN, JAVA, .NET and so on. However, only a few of these development environments met our requirements. They were Visual Basic, Visual C++, and Visual Basic Applications for AutoCAD. Out of these environments, we chose Visual Basic 6.0 as the environment to develop this project. The software tool to automate scheme preparation was then developed in this environment.

5. SYSTEM DESCRIPTION

The software tool requests the user to open an AutoCAD file. The program also requests the user to pick up all corner points of the slab, for which the user wants to prepare the scheme drawing. The program captures the coordinates of the picked points and keeps it in memory up to end of the program, and uses these coordinates for logical decision making.

Standard size/shaped formwork elements are created in AutoCAD and converted into AutoCAD blocks. The Visual Basic program can insert single or multiple copies of these blocks into any AutoCAD drawing.

The Visual Basic program considers all functional and logical requirements of the formwork systems to get an optimized solution, and decides the block profile and where each block has to be inserted in the drawing. While inserting the standard sized/shaped formwork elements into the AutoCAD drawing, the software tool counts the quantities of all formwork elements and displays it as a summary bill of quantities at the end. Screen shot of the application is shown in fig 1.

5.1. Functional Relations between Different Formwork Elements

The following are the some of the functional relations between the formwork elements that were used in the algorithm.

i. Two types of standard sized formwork elements are considered. These are

rectangular elements of 450x900 mm and 450x1100 mm dimensions respectively.

ii. Aluspan beams (Aluminium beams that span an entire column of formwork elements) are required at the end of each column of formwork elements because these are the structural elements, which transfer the load from the slab panels to the props.

iii. For the entire width of a column between aluspan beams, the same type of slab panels (same length) should be placed.

iv. Adjustable slab panels are placed at the end of the each column (same length as other slab panels in the column). If the gap available is less the 450mm and greater than 200mm then adjustable slab panels are recommended. If the gap is less than 200mm, then custom sized slab panels are recommended.

v. A slab corner (100 mm width and 125mm depth) should be placed along all walls (in the inside face of the room). The slab corner is the connector between the wall formwork and the slab formwork.

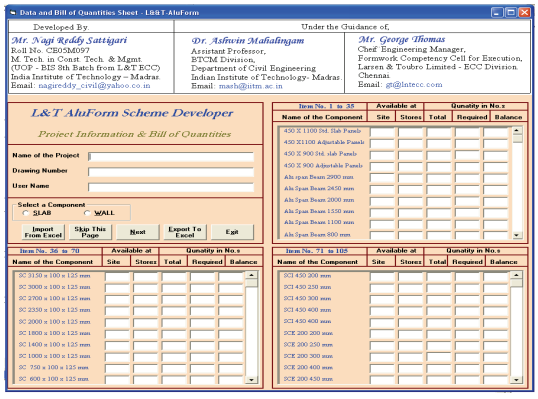


Figure 1 Screen Shot of Data & Bill of Quantities Sheet of L&T AluForm Scheme Developer

5.2. Optimization Technique

In several industrial applications one is required to allocate a set of rectangular items into larger rectangular standardized stock units by minimizing the waste. In wood or glass industries, rectangular components have to be cut from large sheets of material. In warehousing contexts, goods have to be placed on shelves. In newspaper paging, articles and advertisements have to be arranged in pages. In these applications, the standardized stock units are rectangles, and a common objective function is to pack all the requested items into the minimum number of units: the resulting optimization problems are known in the literature as "two-dimensional bin packing problems (2BP)". In other contexts, such as paper or cloth industries, we have instead a single standardized unit (a roll of material), and the objective is to obtain the items by using the minimum roll length. These problems are then referred to as "two-dimensional strip packing problems (2SP)" [3].

In our case, the requirement is to allocate a set of smaller rectangular items into a larger shape (it may be of any size and shape). This is nearly similar to the "two dimensional bin packing problems (2BP)". However our problem has the following significant deviations from 2BP.

i. The larger shape may be of any size and shape in case of this project, whereas it is a standard rectangular shape in 2BP.

ii. For our purposes, the set of smaller rectangular items must fulfil functional relationships between them when placed, whereas in 2BP, when there are no such constraints, one can orient/rotate and accommodate them at any location in the larger rectangular standard shape.

iii. In our problem, multiple copies of the set of smaller rectangular items have to be accommodated. A-priori, we do not know how many pieces we need. In 2BP, only one set of the given rectangular items have to be accommodated in the larger rectangular standard shape.

iv. The area of the uncovered portion of the large shape should be as small as possible for our project i.e. one has to use as many copies of the set of smaller rectangular items as possible to minimize the unoccupied area of the large shape. In contrast, in 2BP, the given set of the

smaller rectangular items (only one set, no copies) have to be accommodated in the minimum area of the given larger rectangular standard shape.

From the above mentioned deviations, one can conclude that the optimization techniques used for two dimensional bin packing problems cannot be directly used, but have to be modified. Blending different techniques, a trial and error method with some modifications is suggested.

In this technique, the program calculates the number of columns of standard sized formwork elements for different formwork types and sizes i.e. no of columns it can place, if it places only 450X1100 mm slab panels or if it places only 450X900 mm slab panels. Then it calculates the end gap by arranging different combinations of 450x1100 and 450x 900 slab panels, and finds out the combination(s) which give the minimum end gap.

The combination, which gives the minimum end gap, is the optimized solution for the shape. In case of irregular rectangular shapes, the program divides that shape into small virtual rectangular shapes and finds out the combination for each virtual rectangular shape. The flowchart for this technique is shown in Fig 2.

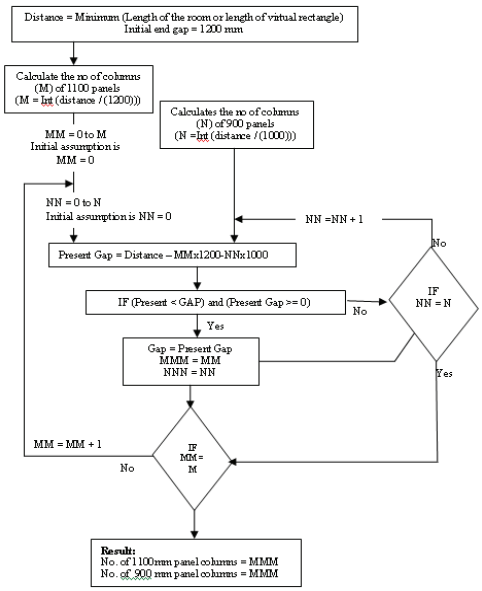


Figure 2 Flow Chart of Optimization Technique

The work procedure for slab formwork and its optimization flowchart are explained with the help of a schematic diagram for a simple slab given in Fig. 3. The algorithm first divides the entire area into rectangular sections. Each section is analyzed separately.

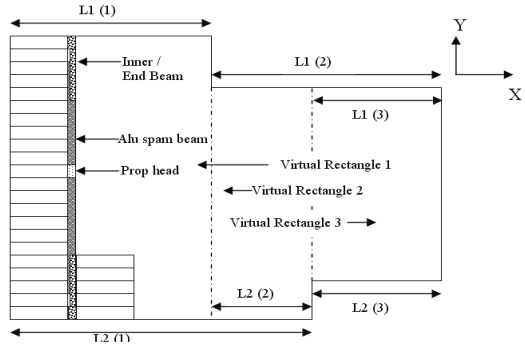


Figure 3 Slab Formwork with L&T-AluForm

An example of a rectangular section is shown in Fig 4 and is titled "Virtual Rectangle 1". For this example section it is possible to place 3 distinct 450X900 panels or 2 distinct 450X1100 slab panels. The algorithm calculates the end gap by first assuming that 450x1100 panels are not used and by placing as many columns of 450x900 panels as possible. Then the algorithm increases the number of columns of 450x1100 panels by 1 and calculates the end gap. This iteration continues by decreasing the number of 450x900 panel columns and increasing the number of 450x1100 panel columns until there are no columns of 450x900 panels. A Schematic diagram for the optimised solution for slab formwork is shown in Fig 4.

The algorithm calculates the end gap for all possible combinations of the 1100 and 900 slab panels. The combination(s), which will minimize the end gap is/are the optimized solution(s). For virtual rectangle 1 of Fig. 4, the minimum end gap corresponds to the placement of 3 distinct columns of 450x900 panel forms. This is the optimized formwork scheme for this example.

6. VALIDATION

The developed software was validated with four cases taken from two ongoing projects. Scheme drawings prepared by the software tool were

compared with manually prepared scheme drawings. In particular we compared the area occupied by standard sized panels in the scheme drawings generated both manually and with the software. Scheme Drawing Prepared manually for Case Study 2 is shown in fig 5. Scheme Drawing Prepared by the Software Tool for Case Study 2 is shown in fig 6.

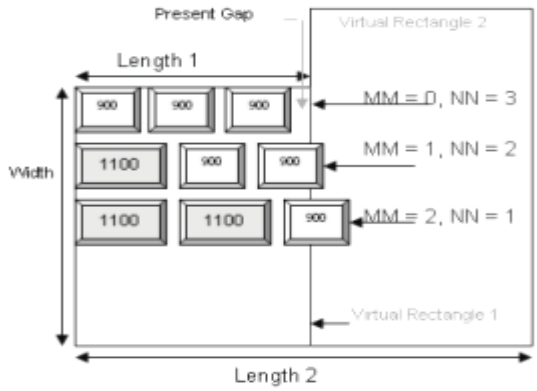


Figure 4 Schematic Diagram to Find an Optimized Solution for Slab Formwork

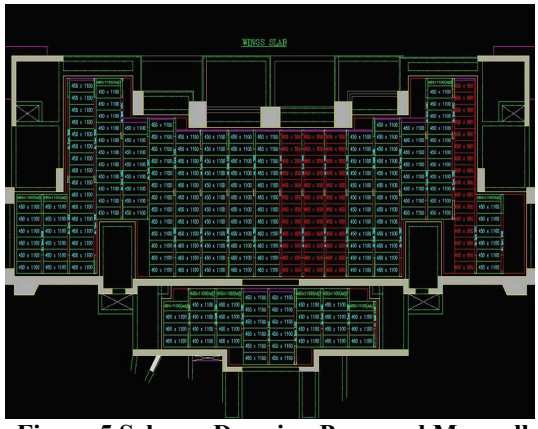


Figure 5 Scheme Drawing Prepared Manually for Case Study 2

A summary of the validation experiment is presented in table 1. The software tool was seen to fill 69.04% to 76.13% (an average of 71.66%) of the total formwork area by placing standard sized slab panels. In contrast, in the manual method that range was 63.46% to 69.63% and the average is 67.35%. Therefore by using the software tool, the usage of standard sized slab panels increased by 4.31% (on average) with respect to the total area of formwork, and by 6.40% (on average) in comparison to the area of standard sized formwork elements in manual scheme preparation.

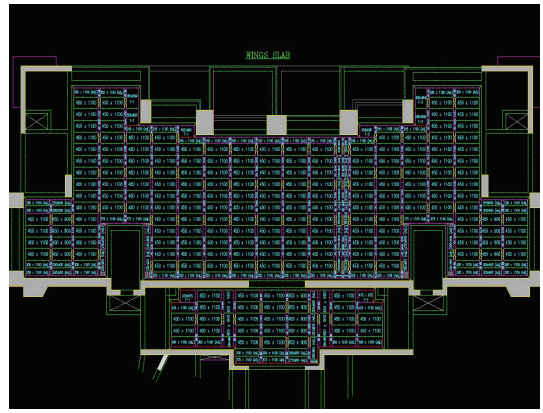


Figure 6 Scheme Drawing Prepared by the Software Tool for Case Study 2

Table 1 Summary of Validation Results

	Formwork	Area of Std panels		Percentage area of Standard panels		Savings	
Case	AREA (Sqm)	Software Tool	Manual	Soft-ware Tool (%)	Manual (%)	w r t (FW area)	w r t (man-ual)
1	109.196	76.320	69.300	69.89	63.46	6.43%	10.13%
2	152.493	116.100	102.420	76.13	67.16	8.97%	13.36%
3	144.047	101.655	100.305	70.57	69.63	0.94%	1.35%
4	127.878	88.290	87.345	69.04	68.30	0.74%	1.08%
Total	533.614	382.365	359.370				
Average				71.66%	67.35 %	4.31%	6.40%

7. DISCUSSION OF THE ADVANTAGES OF THE SOFTWARE APPLICATION

i. Greater usage of standard sized formwork elements

Area occupied by standard sized formwork elements is increased by around 13% for complex shapes and is around 1% for simple rectangular shapes. This means that usage of standard size formwork elements is increased

by 13% for complex shapes and 1% for simple rectangular shapes.

ii. Improvement in readability of scheme drawing

Scheme drawing developed by the software tool is more easily readable and implementable because, the orientation of standard size slab panels are same for entire shape making very easy to read and understand the drawing, where as in general in manual drawings the orientation is in both (x, y) directions in one shape making the users refer very frequently to the drawings while executing the job. 450mmx1100 mm panels are showed in green colour and 450mmx900mm panels are showed in red colour in scheme drawings developed by the software tool, where as all slab panels are in one colour in manually developed drawings.

iii. Reduction in fabrication Costs

Generally, each custom panel is unique because of its size and shape, so each custom panel needs to be designed separately and needs to represent the design detail in the fabrication drawings. Therefore time consumption for the fabrication of a custom panel is more than the time consumption for a standard panel. Semi Skilled technicians are sufficient to fabricate standard panels whereas skilled technicians are essential for the fabrication of custom panels. The software tool utilizes more number of standard sized formwork elements. Thus it will reduce the area for custom size/shaped formwork elements and consequently reduce fabrication costs.

iv. Reduction of lead time between drawings received and execution

The software tool can develop the scheme drawing for a given shape in a couple of minutes, whereas the manual method consumes more than one hour for the same drawing. Lead time between the drawing received to develop scheme drawings and drawings released to the site for execution will definitely reduce if one uses the software tool.

v. Elimination of errors in BOQ Calculations

The tool counts the formwork elements while inserting the standard panels in the given drawing. Therefore there is no likelihood for errors to be made in the calculation of the Bill of Quantities. In contrast, in manual methods, there is a larger scope for errors in the BOQ, because the user has to count each formwork element manually.

vi. Reduction in effort required from the user

User has to open a relevant drawing file and pick all the corner points of the slab/wall to develop the scheme drawing by the software tool. Software tool inserts/places standard panels and leaves areas for custom panels, which the user has to insert. In the case of manual method each and every element has to be placed by the user.

The software tool developed to automate the scheme preparation and BOQ calculation is more useful for complicated structures than simple structures. For simple shapes, it saves only in terms of time consumption but for complex shapes, it saves in terms of material reuse, time consumption and fabrication costs.

8. CONCLUSIONS

Selecting the right developing environment is the key to software development. We used Visual Basic 6.0 as a development environment to develop a software tool for "**Automation of scheme preparation and BOQ calculation for L&T AluForm**". This tool has been named as the "**L&T AluForm Scheme Developer**".

This tool to develop the scheme drawings for slabs, has been validated with four cases taken from two ongoing projects. We carried out some sensitivity analysis on our validation experiment and found that the improvement in the usage of standard sized formwork elements through using the software was of the order of 10% to 13% for complex shapes (cases 1 & 2) and only 1% to 2% for simple shapes (case 3 & 4). This indicates that the software is more useful for complex, non-rectangular shapes, where several scheme layouts are possible and arriving at an optimized layout is non-intuitive.

The developed software – "L&T AluForm Scheme Developer" - has the following advantages over the conventionally used manual method of scheme preparation for L&T AluForm.

- Allocates more no. of standard size panels.
- Greatly improves readability of scheme drawings.
- Reduces fabrication costs / time for custom panels.
- Quickens scheme preparation.
- Automates BOQ calculations.
- Eliminates the need to employ high skills to produce scheme drawings.
- Reduces effort required from the user.
- Facilitates easy explanation/execution at site level.

9. LIMITATIONS

This software tool also has some limitations that are discussed below.

i. This tool has some geometric limitations, i.e. this tool works well for regular/irregular rectangular/square shapes but it cannot develop schemes for curved or inclined shapes

ii. Tool cannot allow the user to withdraw any point picked (as a part of the input) from an AutoCAD drawing.

iii. The current version of the program cannot automatically insert custom sized/shaped slab panels. The user will have to manually design and place custom shaped slab panels in the designated areas.

iv. We have used a trail and error algorithm to find the optimised solution. This algorithm can give very fast results for slabs of lengths of around 30m. However, for longer slabs, performance of the system with respect to time will decrease (processing time will increase). Perhaps a better algorithm can be developed.

10. SCOPE FOR FUTHER DEVELOPEMENT

An automated tool to develop the schemes for slab has been developed and has been shown to have practical benefits in terms of cost, time and effort savings. Future work could include developing tools to deal with walls with openings, columns, beams, sunken slabs, stair cases, and any other special structural elements of buildings. The L&T-AluForm scheme developer has some (above mentioned) limitations. Future work can overcome these limitations.

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A COMPUTER-AIDED SYSTEM FOR PLANNING AND 3D-VISUALIZATION OF MULTIPLE HEAVY LIFTS OPERATIONS

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ABSTRACT

Planning multiple heavy lifts on heavy industrial projects has a major impact on construction sequencing, scheduling, budgeting and safety. Hence it has to be planned carefully to reduce the risk and to reduce the cost and duration of the projects. Traditional planning techniques are quite unproductive as they use iterative and trail and error techniques. This paper discusses the work done towards development of computer aided multiple heavy lift planning system. The features of the software tool developed on AutoCAD platform includes- selection of cranes, crane location identification, 3D simulation of the multiple lifts and 4D representation of the site. The system developed is evaluated by using a case study. The features of the software like crane location, 3D simulation are evaluated using 25 lifts.

KEYWORDS

Multiple Heavy Lift Planning, 3D Simulation, Cranes, 4D CAD

1. INTRODUCTION

Cranes are commonly used equipment in almost all the industrial construction and maintenance operations. Particularly in erection projects like power plant erection, blast furnace erection projects etc. cranes are the central lifting equipment. With the introduction of heavy lift cranes, it is becoming more common to reduce plant equipment fabrication costs by fabricating larger portions of equipment at specialized off-site fabrication shops. While the fabrication costs and efforts are streamlined, more effort is required to plan and lift these mammoth modules into place. Large industrial projects involve the erection of many vessels on one project site. The multiple heavy lifting process requires months of planning using traditional methods. Inadequate planning of this activity can sometimes lead to costly damages in terms of lives of construction labour and damage to other operating facilities. This work attempts to develop a computer aided heavy lift planning system, which can improve the productivity and reliability of the multiple lifts planning process.

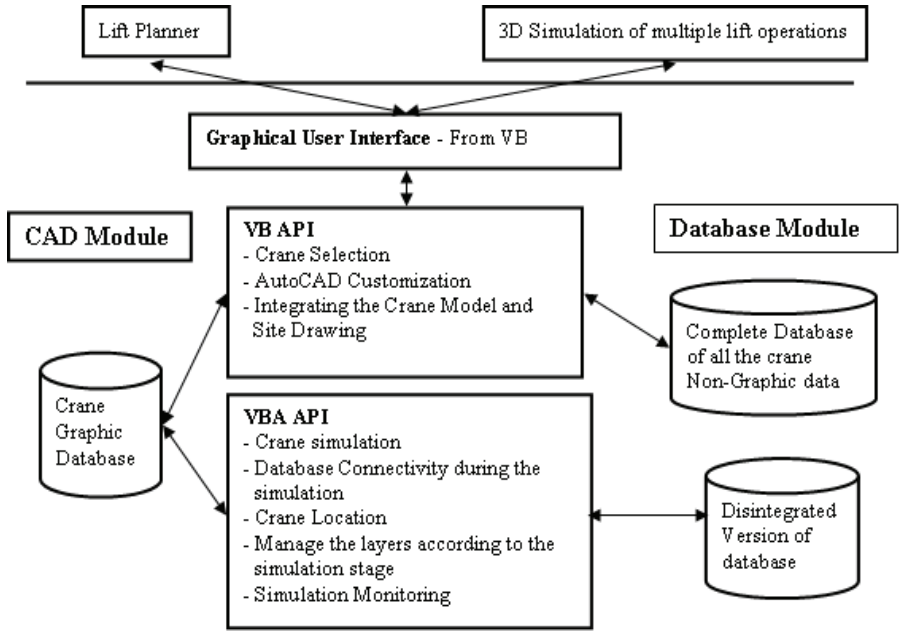


Figure 1 Multiple Lifts Planning System Architecture

2. BACKGROUND

Previous research on heavy lift planning has focused on single lift simulation, multiple crane locations optimization, crane selection and path planning.

HeLPS (Heavy Lift Planning System) [1] has demonstrated the simulation of single lifts while Lin. K [2] proposed an interactive computer-aided process to optimize crane locations for multiple lift situations. Arriving at an optimal solution using the present studies and tools is not possible as they do not provide a common platform for multiple lift decision-making. Hornaday [3] has presented the detailed analysis of a computer-aided lift planning requirements. Multi-dimensional design technologies have been proven to be very helpful to improve the way the planning is done, to communicate the designs and erection sequences. One such successful application is 4D CAD. Though such 4D CAD models are helpful to some extent in visualization, they do not give any information on where the crane needs to be, at what point in the schedule, and should be erecting which vessel. Hence the present work aimed to develop a multiple lifts planning system with the features like 4D CAD, crane selection, crane location for multiple lifts and multiple lift simulation etc.

3. SYSTEM ARCHITECTURE

AutoCAD® 2007 has been chosen as the application platform. AutoCAD is customized using VBA API to create the multiple lifts planning environment. Fig.1 shows the importance aspects of the system architecture. The interface to select the crane for the given lift parameters like boom length, operating radius and weight of the load is developed in Visual Basic. VB interacts with the database to search the feasible configurations for given parameters and lists the feasible configuration.

The database module consists of two databases- graphic database of crane models and non graphic database containing the load charts. The complete load chart database is disintegrated into the tables of individual crane charts to save time during the search for capacity. The graphic database of cranes consists of CAD models of 10 crane configurations of lattice boom crawler and heavy lift (ringer) cranes drawn to scale. VB builds the custom toolbar and assigns the corresponding modules in the dvb file for manipulating the DoFs of crane, changing the boom length, and crane location

module. The dvb file forms the core of the simulation part. It contains modules of the user defined subroutines and functions to perform the different operations of manipulating the cranes Degrees of Freedom (DoFs) and crane location. VBA interacts with database to identify the minimum and maximum operating radius of each vessel to identify the crane location from the intersecting regions.

Once the crane locatable region is identified; the user can start the simulation starting with the first stage and subsequently can do the other lifts simulation according to the sequence of erection. The VBA module defines the master-slave relationship and loads the selection sets accordingly on which the operations like rotate, move etc. are performed.

4. KEY FEATURES

The present multiple lift planning tool assists the lift planner with the following features:

4.1. Crane Selection

Multiple lift planning system assists the lift planner to select the crane according to the required parameters for the lift. A list of feasible cranes that satisfies the given lift parameters will be listed. The user can check feasible crane for all the lifts and can select a crane based on availability for simulation to check the clearances and capacity.

4.2. 4D Representation of Site

The communication of the design and erection sequence of the plant requires either creation of a prototype of the project layout or development of some kind of graphics animations. The present tool can replace the use of such techniques by the representation of the site as a 4D model. The site details are organized in layers according to the stage of erection. By turning the layers off and on the site can visualized according to the schedule.

4.3. Manipulation of Cranes DoFs

The customized AutoCAD environment provides the toolbar based interface to manipulate the degrees of freedom of crane and to virtually operate the crane on the 3D model of the site.

The crane operation can be simulated to visualize the lift path between the pick and place location. Fig 2 shows the different degrees of freedom of the crane that can be manipulated.

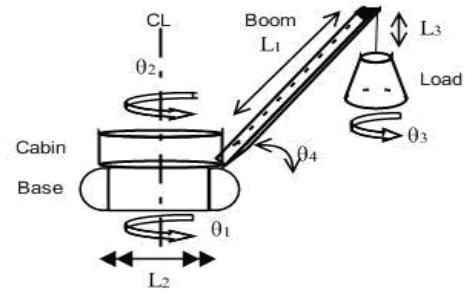


Figure 2 Different Degrees of Freedom of the Crane and the Vessel that can be Manipulated

4.4. Crane Location

One of the key decisions that control the lift planning process of the multiple lifts is the crane location. Work envelope concept proposed by Lin et al. [2] is used to implement the crane location module. Lin has considered the spatial and capacity constraint to identify the interference free work envelope. This method has left the envelope of the crane with interferences unexplored for the possible paths between the pick and place location in the interference region. Hence in this case, the work envelope is drawn for capacity constraint only and the feasibility of the crane location is checked using the 3D Simulation. The user is prompted to enter the details like Vessel ID, Vessel Weight including the weight of the rigging attachments and type of rigging attachment and the stage to which the vessel belongs to. Once the user enters the data, the crane locator module displays the window to select load ID and the choice of boom length for identifying the crane location. This module displays the locatable region for each lift. With a little interpretation using the boolean operation like intersection, the user can identify the crane locatable region for any number of lifts.

The advantage is that it avoids the repetitive task of finding the crane location by conventional multiple lift planning process.

4.5. 3D Simulation of Multiple Lifts

Multiple lifts that are lifted in logical sequence can be simulated to check the lift plan and to visualize the potential hindrances to the lifting activity. The present tool provides the feature to simulate any number of lifts. The user can do it sequentially by organizing the site in different layers according to the erection stage. The capacity is continuously monitored during the lift path planning from the database and the percentage capacity is displayed to check if the capacity is exceeding the certain percentage which can be considered as risk.

5. MULTIPLE LIFT PLANNING PROCESS USING THE SOFTWARE DEVELOPED

The sequence of steps to be followed to plan the multiple lifts is shown in Fig. 3. In the first stage, the lift planner needs to initially identify the erection sequence of the vessels. The list of cranes that can do all the required lifts is displayed based on the capacity constraint. The user can then select the list of cranes for further planning after filtering against the subjective criteria like crane availability and access to the site.

In the stage 2, the lift planner should initially identify the crane configuration for each lift and should minimize the configurations of a crane using his reasoning ability. 3D simulation can be used to provide visualization for the user to identify the different configurations and minimize their number. Once the crane configurations are finalized, in the next stage the user needs to find the crane location for all the lifts using the crane location module.

These locations are based only on the capacity constraint and therefore are needed to be checked for adequate clearances, which can be done using 3D simulation. If the clearances are adequate, the user can perform the simulation of all the lifts to check the feasibility of the overall lift plan.

If the clearances are not adequate, the user can go back to stage 2 where the crane configuration should be reselected and location should be identified for the new configurations. The alternatives for crane locations can be evaluated by the user with cost, safety and project duration as the criteria. Once the minimum number of crane locations and the configurations are identified, the user can finally check the lift plan for feasibility and plan the path between the initial and final positions for each vessel. The user can record the simulation in a video format and generate the 2D drawings simultaneously during the simulation.

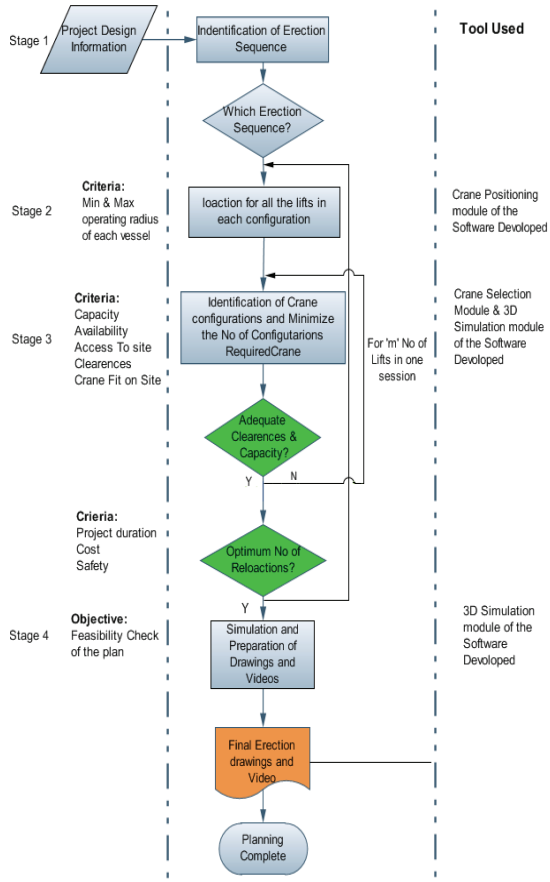


Figure 3 Multiple Lift Planning Process

6. EVALUATION

A case study of Blast furnace erection is used to evaluate the system effectiveness and its value in planning the multiple lifts.

The maximum height up to which the erection was required was 90 m and there was very limited space for assembly of the components. The site congestion was a key constraint for lifting activity and the lifting involved erection of vessels as

heavy as 150 tons in a single lift. So, the lifts can be considered 'Critical'. The project required the erection of 25 such critical lifts in the furnace area. Fig. 4 graphically illustrates the erection sequence of different vessels and the scope of evaluation. Table 1 shows the erection weight of different vessels.

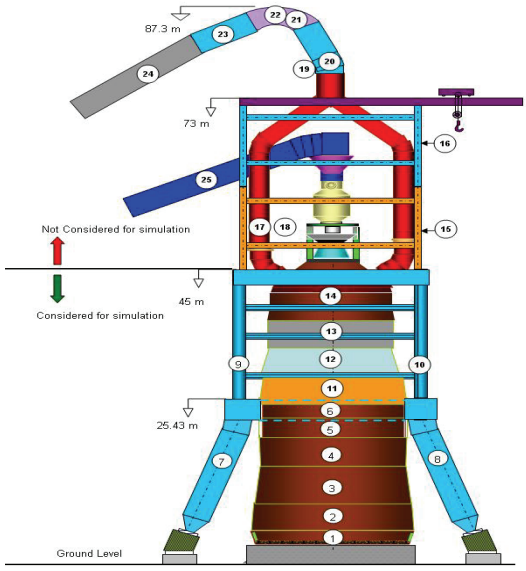


Figure 4 Components of Blast Furnace and Their Erection Sequence

6.1. Preliminary Crane Selection

Initially, the crane selection module has identified two feasible cranes from the database for all the lifts.

Based on the subjective decisions like availability of the crane, access to the site etc., the Link Belt FMC LS1018 ringer crane was not available; hence the further planning was based on the other one, which is the American 9320 ringer crane (A9320).

6.2. Minimize the Crane Configurations

Configuration of a crane includes three important variables- crane model, base type, and boom length. Initially the configurations required for each lift are identified. The cost to be incurred decreases in the order of using more cranes followed by switching the type of base and

Table 1 Erection Sequence and Weight of Different Vessels

Erection Sequence	Vessel	Erection Wt (Kgs)
1	Shell A	86960
2	Shell B	55460
3	Shell C	86180
4	Shell D	90000
5	Shell E	69910
6	Shell F	82070
7	Lower Tower-1(LT-1)	150000
8	Lower Tower-2(LT-2)	150000
9	Middle Tower-1(MT-2)	99000
10	Middle Tower-2(MT-2)	90000
11	Shell G	76320
12	Shell H	72690
13	Shell J	74860
14	Shell K	74860
15	Upper Tower up to 65m	56000
16	Upper Tower up to 73m	30000
17	Offtake-1	55300
18	Offtake-2	55300
19	Uptakes 1	13500
20	Uptakes 2	13500
21	Uptakes 3	14500
22	Uptakes 4	14500
23	Y piece	49000
24	Down comer	35700
25	Charging conveyor	60000

changing the boom length. The first two factors are taken care during the initial crane selection while the third one is minimized in this stage. 3D simulation of the vessels and the lift planners reasoning ability is used to interactively minimize the number of changes to be made in the boom length. In this case, initially the configurations are identified from the elevation required to reach the final location. These are shown in the Table 2.

For example, from the capacity and elevation requirements the shell A to D required a boom length between 42.7 m and 115.8 m while, Shell E and F required a boom length between 54.7 m and 115.8 m. The erection of the lower tower required either 42.7 m or 54.7 m boom length from the capacity constraints. Hence to minimize the configurations the shell A to F and lower tower erection is changed to 54.7 m boom length. The crane locations and the corresponding configurations are finalized for capacity constraint and the clearance is checked during the 3D

simulation. Similarly other configurations are finalized. Table 3 shows the final configuration for the American 9320 ringer crane after the two iterations of simulation. As the simulation module is used for only 14 out of 25 lifts, the vessels 15 to 25 are planned with the maximum boom length so that it will not effect the decision of the crane location due to inadequate clearances, because the clearance between the boom and the vessel increases as the boom length increases. Once the crane configurations are finalized the crane location is found out using the crane location module.

Table 2 Initial Crane Configurations American 9320 Ringer Crane

S. No	Vessel	BL (m)	S. No	Vessel	BL (m)
1	Shell A	42.7	8	LT-2	54.9
2	Shell B	42.7	9	MT-1	67.1
3	Shell C	42.7	10	MT-2	67.1
4	Shell D	42.7	11	Shell G	79.2
5	Shell E	54.9	12	Shell H	79.2
6	Shell F	54.9	13	Shell J	79.2
7	LT-1	54.9	14	Shell K	79.2

Table 3 Final configurations for American 9320 Ringer Crane

S. No	Vessel	BL (m)	S. No	Vessel	BL (m)
1	Shell	54.9	8	LT-2	54.9
2	Shell	54.9	9	MT-1	67.1
3	Shell	54.9	10	MT-2	67.1
4	Shell	54.9	11	Shell G	97.5
5	Shell E	54.9	12	Shell H	97.5
6	Shell F	54.9	13	Shell J	97.5
7	LT-1	54.9	14	Shell K	97.5

6.3. Crane Location

The objective of the lift plan is to achieve the erection of multiple lifts with minimum number of changes in boom length of a crane at minimum number of locations. In the present case, for the A9320 crane the crane location is done for all the 25 lifts by using the crane location module. The crane locatable region for all the vessels is shown in Fig. 5. The intersection boolean operation is used to find intersecting regions. The AutoCAD drawing showing the final regions is shown in the Fig. 6. The crane selection module has identified **two** crane locations for the erection of all the 25 lifts. The location 1 has two options on each side of the blast furnace. The option-1 shown in Fig. 6 is chosen because; at this location there is adequate space for the assembly. These crane locations in terms of the relative coordinates are shown in Table 4.

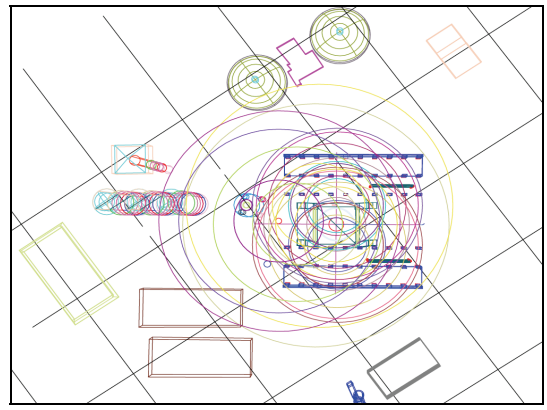


Figure 5 Crane Work Envelopes for All the 25 Vessels

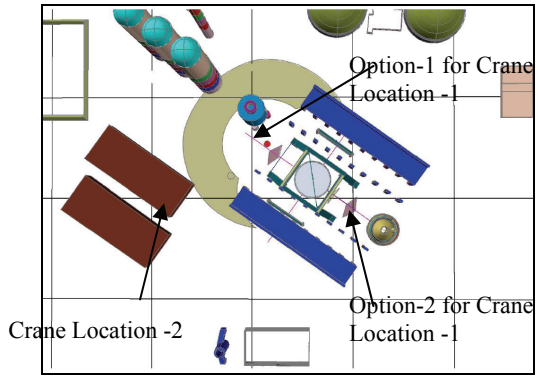


Figure 6 Crane Locations for all the 25 Lifts

6.4. 3D-Simulation to Check the Clearances and Capacity

Once the crane location and the configurations are identified, these should be re-checked for adequate clearances and capacity. The 3D simulation

module demonstrated that the A 9320 ringer crane can adequately perform all the lifts with sufficient clearances and capacity at the locations identified by the crane location module with the configuration identified as shown in Table 3. The simulation was performed for each vessel of the 14 vessels considered. Fig. 7 shows the simulation environment of the software.

Once a stage is simulated, the user can perform the next stage simulation by selecting the stage and the vessel in that stage. Each stage can have as many number of vessel erections as required. The site will be dynamically changed when the simulation is performed between the stages for better visualization of the complete process. The sequence of actions performed by the user during the simulation is recorded in a text file. These can be used during the final erection as a guideline for

Table 4 Crane Locations Identified by Using the Crane Location Module

Location No	Crane Location Coordinates		Vessel to be lifted in the location
	X	Y	
1	E- 1801.20	S-605.88	Shell A to G Lower Tower Middle Tower Upper tower Offtakes Uptakes
2	E-1739	S-581.1	Down Comer Y-piece Charging Conveyor

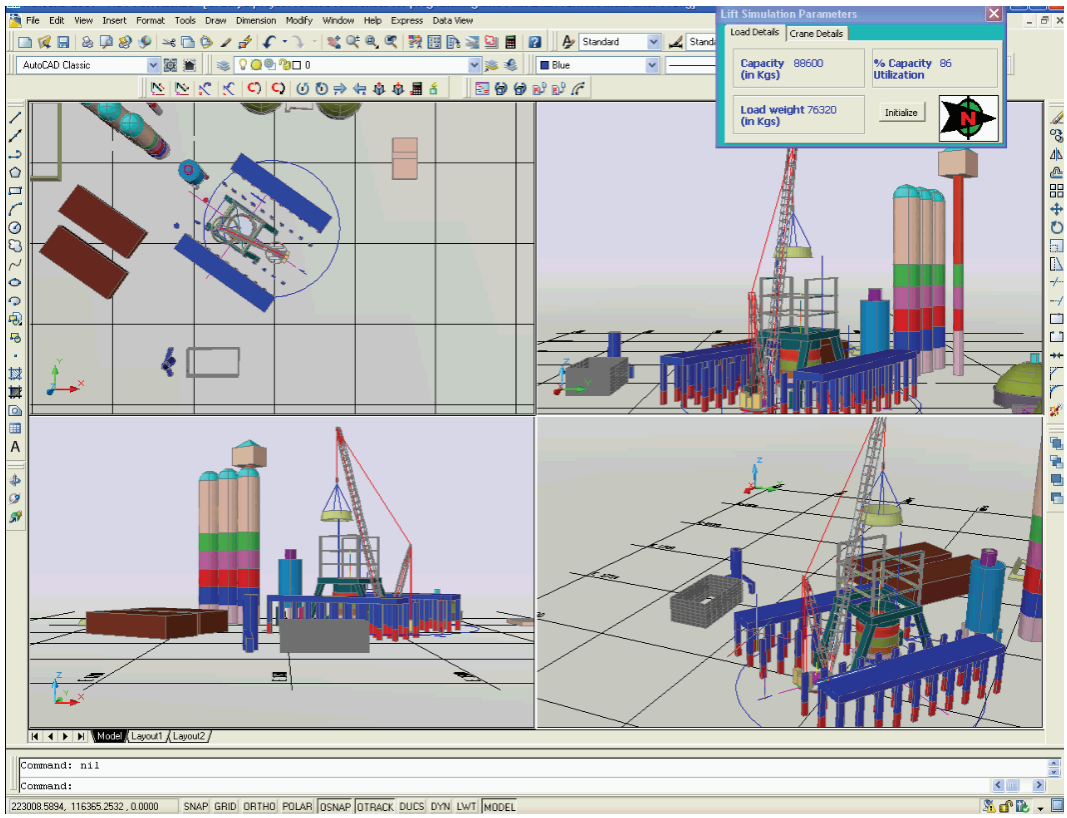


Figure 7 Multiple Lift Planning Software's Simulation Environment with the Monitoring Window

the crane operator or as input to the robotic cranes to automate the crane operations completely on the site. Also the video of the simulation is recorded to communicate the lift plan. The proposed method of lift planning proved to be not only productive and reliable but also the guesswork can be completely eliminated thus saving time and on-site feasibility testing.

7. CONCLUSIONS

Automation of the some of the key decision variables of multiple lift planning like crane selection, crane location can significantly improve the productivity of the multiple lift planning process. The multiple lift planning system developed on AutoCAD platform provided an easy and fast planning interface with the unique features like crane selection, crane location automation for multiple lifts, 3D simulation of multiple lifts and 4D representation of the site.

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DEVELOPMENT OF A 4-D MODEL FOR APPLICATION IN CONSTRUCTION MANAGEMENT

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ABSTRACT

Planning for construction projects faces challenges due to complexity in design and short deadlines. Further, very limited tools are available to planners for integrating the visual representations of site with the progress of time, which results into their relying on experience and imagination to decide the appropriate sequence of construction plan. In the study, the 4D Model has been developed with the hope that it will allow the planners to visualize the construction with the passage of time at the planning stage itself without even starting the work in reality and thereby removing the flaws that might have been left out in the construction project plan. The model has been tested for a simple construction due to paucity of time. However the results obtained are encouraging. It has the potential to show potential conflicts in a construction site and is capable to perform what-if analysis which may finally lead to the improvement in project planning and project executing strategy.

KEYWORDS

4D Model, Project Planning, Progress Tracking, AutoCAD, MS Project

1. INTRODUCTION

The position of a point in space is defined by the coordinates (x, y, z). When all the elements of a structure are defined in space with the help of their 3d coordinates, the result is a 3D model of the structure. When the position of the point with respect to time is not fixed or in case the point is changing its position with time, then we need to consider another dimension, the fourth dimension 'time' and the resulting model is known as 4-D model.

During the past decades, advances in three-dimensional (3D) computer-aided design (CAD) technologies have furnished the opportunity for planners to apply 3D models to manage construction information in projects, by way of viewing their static realistic images. However, these 3D models by themselves, without the ability to display the exact status of a project at a specified period, furnish little assistance in progress control. There are no data integration and interaction between the 3D model, schedule information and other data. In order to produce a construction schedule from 3D drawings, planners have to envision the sequence of construction in their mind.

Construction projects are dynamic in nature and as the time progresses the status of construction progress also changes. However, most managers plan their projects based on the preliminary site layout and utilization drawings which frequently gets updated during the execution of project. A 3D model for such situations generally does not capture the reality and the need for a 4-D model which can incorporate 'time' also into account would be very much desirable. The 4D model not only provides the visual aid in depicting the structure as the time progresses, it also poses numerous other advantages, such as capability of

performing what-if analysis, viewing the structure from different angles etc.

In this paper, the authors have linked 3D model of the structure and construction schedule of the project, so that the status of the project can be reviewed in the form of 3D model of the structure at any instance of time. For developing this program AutoCAD has been used for generating the 3D model and Visual Basics has been used for providing interface and generating the user friendly input window.

The model so developed could assist the planning managers in visualization of the details of the prospective work at any specified time. This could further lead them to take better decisions both during the planning and construction stages.

As mentioned above 4-D model has wide applicability in construction industry, the present study however focuses on developing the model which allows project stakeholders to view the planned construction of a facility over time on a computer screen and to review the planned or actual status of a project in the context of a 3D CAD model for any day, week, or month of the project.

The paper has been organized in number of sections. In the next section we review the literature relevant to the study area and then present the research methodology adopted to achieve the stated objectives. The description of the model with an illustration follows next. At the end summary and conclusions are provided.

2. LITERATURE REVIEW

During the past decade, research efforts have been made towards advanced four-dimensional (4D) planning models by integrating three-dimensional (3D) visualization with the time attribute.

Koo and Fischer [1] showed that 4D models are effective in evaluating the executability of a construction schedule and highlighted the need for improvements to 4D tools through a case study. They concluded that 4D models are a useful alternative to project scheduling tools like CPM networks and bar charts. The case study also highlighted the need for improvements to 4D tools.

Dawood et al. [2] presented the report on the development of an integrated database to act as an information resource base for 4D/VR construction process simulation. A comprehensive database was designed, implemented and populated with the School of Health Construction Project. The database is composed of a core database of building components which is in turn integrated with AUTOCAD 2000, MS Project and Graphical User Interfaces. The core database was designed using Standard Classification Methods. Integrated interfaces between MS Access database, AutoCAD drawings and MS Project Schedules were developed and implemented.

Chau et al. [3] discussed a 4D visualization model that is intended both to help construction managers plan day-to-day activities more efficiently in a broader and more practical site management context. Mallasi and Dawood [4] reported on the development of site –PECASO model as part of their ongoing project. The Site-PECASO model provides project planners with a product-oriented simulation tool that highlights spatial clashes and interference between construction operations in real-time 4D environment. Chau et al. [5] discussed some insight and experience on the on-site use of a prototype 4D site management software system for a warehouse superstructure in Hong Kong. The system links a three-dimensional model and a construction schedule to furnish visualization of the state of a site at any user-specified date. Through site trial, some limitations of the software are also spotted which consequently lead to enhancement to the system. Sadeghpour et al. [6] presented an interactive computer-aided site layout model to support site planning in a computer-aided design (CAD) environment. The model offers three tiers of objects: (1) site objects, (2) construction objects, and (3) constraint objects. The structure facilitates the creation of new objects and reuse of domain knowledge, which allows for the gradual expansion and enrichment of the model's knowledge base. The model is structured in three main modules: Database, Project Module, and Layout Control Module. The functionality of each module, along with their interconnectivity is described. The model is implemented using Visual Basic for applications in AutoCAD environment and

Microsoft Access. Chau et al. [7] delineate the development and implementation of a prototype four-dimensional site management model (4DSMM), with the objectives to address the requirement for linking scheduling data to a three-dimensional computer graphics building model and to furnish the capability for planners to view graphic simulations of the construction process at any prospective specified date.

Lena and Osama [8] discussed the utilization of CAD technologies to establish effective integration in a number of construction management functions. A CAD-based project management methodology is achieved by making use of the AutoCAD features that allow the designer to associate graphic objects with extended data stored in a central database. The system further integrates the database with commercial project management software that becomes the interface for construction management functions including, planning, scheduling, and cost estimating. Arun et al. [9] developed a methodology for integrating computer aided design with construction scheduling using standard software application packages namely AutoCAD and MS-Project along with MS-Access database. The integration was achieved by developing suitable interfacing modules.

In the present study, a 4D visualization model for construction planning and site utilization has been developed. The research methodology adopted for the development of model is presented in the next section.

3. RESEARCH METHODOLOGY

The 4D model developed for the study comprises mainly a 3D model of the structure and a construction schedule. In the development of model for the study, the 3D geometrical model of the structure has been prepared using AutoCAD and VBA representing all elements floor by floor, based on the construction method and program proposed by the contractor. Microsoft Project has been used in this model to display a bar chart scheduling environment, and for developing the interface Visual Basic application tool available in AutoCAD has been used. The model developed has been tested on a hostel building.

4. DESCRIPTION OF THE MODEL

The 4D-model provides an information platform that couples the project schedule and dynamic site plan with the structure 3D model to serve the purpose of site management, covering construction planning.

The 4D model program is developed and tested for a two-storeyed concrete framed hostel building for illustration in the paper. The building has been divided into eight grids numbered 1 to 8 in X-direction, and four grids numbered A to D in Y-direction. At each of the grid intersection a reinforced concrete column is there, thus a total of 32 columns exist at each of the floors of the building which adds to 64 column elements for the hostel building. The slab and beam at each floor has been divided into seven elements, thus a total of 14 slab and beam elements for the building. Similarly walls in x-direction and y direction for both the floors combined together add to 108 elements. Thus, the entire hostel building is split into a total of 186 individual elements. These elements are numbered separately, so that after inputting the values, the program calls the element with the same number. The numbering pattern can be seen from Fig 1 also which is the input form of the program and appears after running the program. For ground floor column, the symbols ColF1A to ColF8D have been used while for first floor columns the symbols ColS1A to ColS8D have been used. Similarly the symbols have been kept for wall and slab-beam elements for ground and first floor.

For developing the interface the coding has been done in Visual Basic editor which appears in AutoCAD screen after invoking | Tools | Macro | Visual Basic editor in that order. In the input form shown in Fig 1, the user has to input the tentative date of completion of each activity separately. The user also has to specify the progress period at which the user wants to view the progress. This input form is linked with VB code, to develop the 3D model for different options.

The flowchart of the coding shown in Fig. 2 describes the working of the software. For working on program first the user has to run the program. When the program runs, it generates a window which appears as shown in Fig. 1, then the user has

to input the planning schedule (based on the construction schedule prepared in the M.S. project) and the time at which the user wants to see the progress and the 3D model of the structure.

Then for each element the program checks the planned completion date as per the planned schedule and the date for which progress is required. If the date for the planned completion date of the individual elements is less than or equal to the later one that is the date of monitoring , then the program calls that particular element and generates 3D drawing of that particular element. Similarly the program checks for each element separately and finally the program generates the 3 D model of the structure showing the progress up to that particular date. Hence this way the user can see the 3D model of the structure planned to be completed up to that particular time. At this stage if the user wants to compare the different planning options, then it can also be done by this program just by changing the inputs. For example if the user wants to see the progress on n^{th} day, he inputs the value of 'n' in the space provided in the input form along with the planned date of completion of each of the elements shown in the input form. Once the program is run, it compares the planned input values with 'n' and generates the 3D model of the structure showing planned progress on that date. Some outputs of the program for different values of 'n' and planned completion dates of each of the elements are shown in Figures 3 and 4.

The 4D Model allows what-if analysis to compare the different planning options. In other words, if the user had filled all the inputs based on the initial planning and after seeing the 3D models which the software develops or due to some other reason, the user wants to change the planning, then just by changing the values against that particular elements for which the user want to change the planning, the software again generates the new 3D model based on that new planning.

Another advantage of such models is that images could be rotated for viewing from any desired angle, zoomed as required and shared on the computer network, which is impossible by other available techniques. The 4D model can also assist site personnel during brainstorming sessions on access to site, storage at sites and sequencing of construction activities.

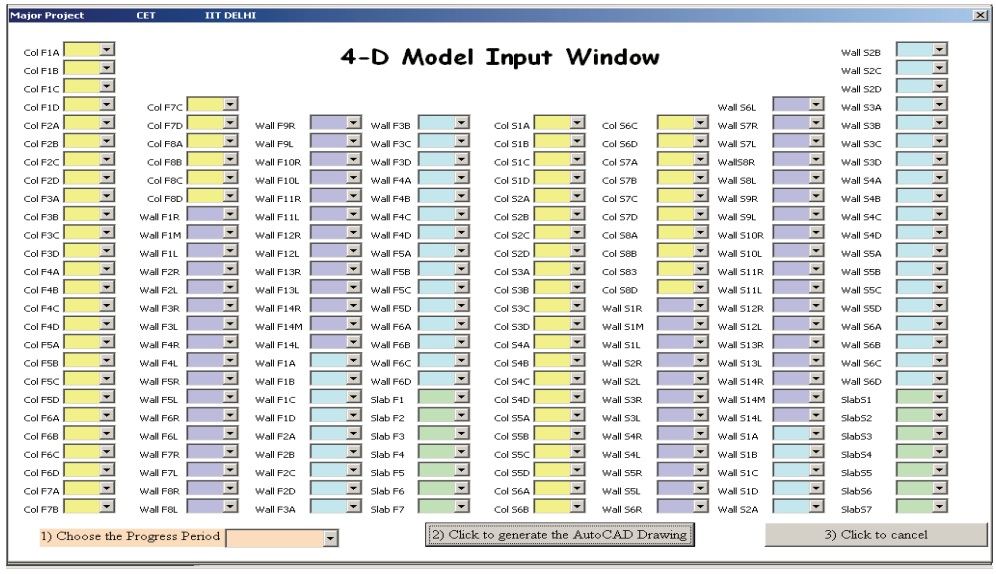


Figure 1 The Input Form

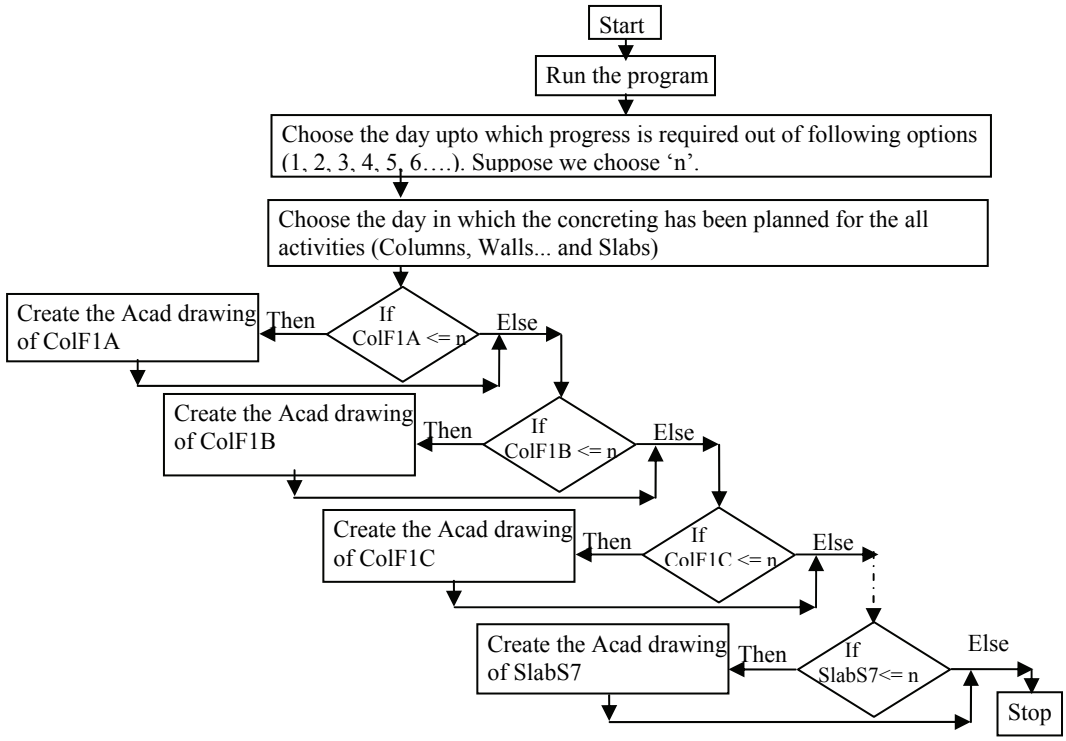


Figure 2 Flow Chart of the Coding

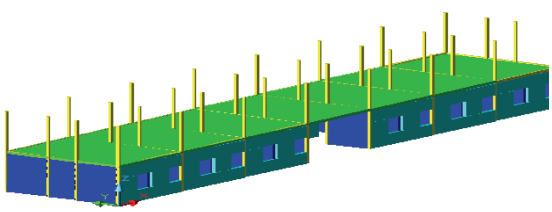


Figure 3 Output at Intermediate Stage

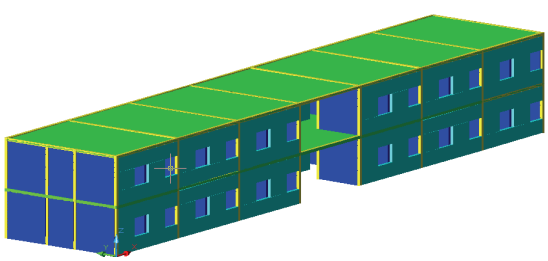


Figure 4 Output at Final Stage

For implementing this software at site, the architect/designer prepares the 3D model and the planning department of contractor is responsible for the preparation of the construction schedule. If there is early collaboration between the two parties, good results can be obtained. However, in actual practice, designers and planners usually work independently with a low degree of co-ordination which may impede the successful implementation of the model. Indeed, the 4D model applications would be assisted by close co-ordination between designers and site planners.

The model described in the paper is the output of an ongoing study and is in preliminary stage. A number of improvements can be made to make it more users friendly. The current model requires a large number of input to be given by the user since it is not compatible with the scheduling software. Further, the model does not provide any information on percent completion of the project currently.

5. CONCLUSIONS

In this paper, a prototype 4D model has been developed and implemented with a view to overcoming problems incurred in conventional construction planning methods and in incorporating practical site management features. This 4D model, which links the 3D geometrical model with scheduling data, comprises the activity schedule and 3D model of site facilities at any projected instant. There are many potential benefits of the 4D model system, including facilitating site planning and management, predicting the occurrence of any potential site problems, and streamlining the site management practices. Moreover, the advancements in computing technology have assisted in this work, resulting in a user-friendly, comprehensive, and integrated site management tool. It is believed that 4D visualization will have strong potential in construction planning and management processes.

Further for successful implementation of the model, close coordination between designer and planner is required. The present weak level of co-ordination can either hinder the application of such software, or else such software itself could, perhaps a bit optimistically, become the means of promoting future co-ordination between designers and site planners.

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THE DEVELOPMENT OF nD CAD

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ABSTRACT

The development of Virtual Design and Construction solutions needs a target- and vision-oriented approach at three levels: international, national and company. This paper provides an overview of both international and typically Dutch initiatives and how they influence developments at company level. As might be expected, it is challenging to match target-and vision-oriented developments. The following questions will be addressed: What are the business drivers? Are these drivers attainable at the company level? What are the technological opportunities and barriers? How are competitive edges defined, and what are the common goals, means and developments at these three levels? Are activities at these levels related from a company perspective? What results can be expected within the next three years?

KEYWORDS

Implementation, Virtual Design, Barriers, Opportunities, Business Drivers

1. INTRODUCTION

Everywhere and at all levels, developments in ICT play a key role in determining development agendas.

This paper provides insight into developments at three levels: European, member state (Netherlands) and company (Royal BAM Group) and in doing so also at policy, tactical and operational level.

2. APPROACH OF THE PAPER

For the development of research policy in Europe, documents from the European Construction Technology Platform are consulted. A wealth of information, mainly on policy, can be found at www.ectp.org [4]. The national association of enterprises, BouwendNederland, shows the approach at national level [2]. The description of Royal BAM Group's activities provides insight into initiatives at an operational level. The description of the activities at these three levels in section 3 is followed by a summary of opportunities and barriers in section 4. Section 5 contains a short delineation of the expectations for the near future.

3. THREE LEVELS OF INITIATIVES

This section describes the initiatives taken at European, national and company levels.

3.1 European Level

The European Construction Technology Platform has formulated a research policy that reflects political, economic and social ambitions.

'The European Construction Technology Platform (ECTP) officially endorsed its Vision for a sustainable and competitive sector by 2030 "Challenging and Changing Europe's Built

Environment" through its High Level Group meeting held on March 1st, 2005 in Brussels. This Vision fulfilled an important need for a long-term perspective on research needs and set ambitious objectives for the sector. 'In the year 2030, Europe's built environment is designed, built and maintained by a successful knowledge and demand-driven sector, well known for its ability to satisfy all the needs of its clients and society, providing a high quality of life and demonstrating its long-term responsibility to mankind's environment. Diversity in age, ability and culture is embraced. Equalisation of opportunities for all is an overarching principle; the construction industry has a good reputation as an attractive sector to work in, is deeply involved in research and development, and its companies are well known for their competitiveness on the local and regional as well as global levels.'

Vision of a sustainable and competitive construction sector by 2030: 'Challenging and Changing Europe's Built Environment'. This Vision identified a number of important and desirable objectives that should enable the development of better technologies, and to raising the level of "sustainability" in the sector. This would occur both in terms of the characteristics of the buildings and infrastructures themselves, as well as in the processes of actually carrying out construction works.

The Strategic Research Agenda (SRA) of ECTP was endorsed in December 2005. Based on the objectives set up in the Vision 2030, this SRA was a first attempt to identify a set of Research Priorities organised along three main goals clearly singled out: meeting clients/users requirements, becoming sustainable and transforming the construction sector.

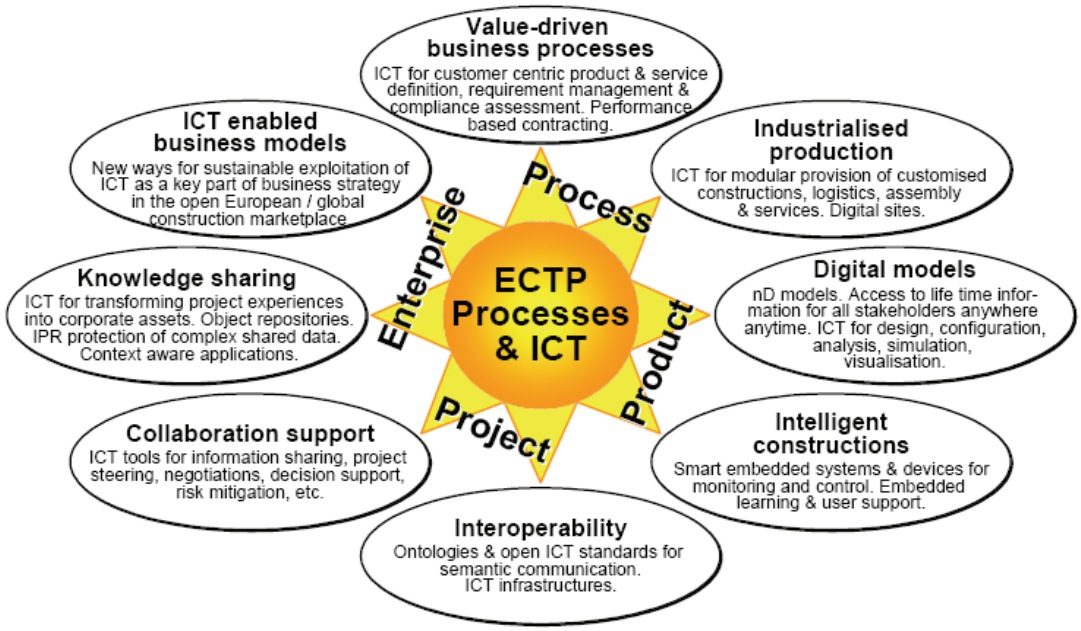
The SRA defines the research that need to be carried out to achieve the vision whilst at the same time taking into account market forces. It is for these reasons that the SRA is inherently difficult to get right and at the same time is a document of crucial importance. Construction is a huge industrial sector that involves more than 2.5 million enterprises. Furthermore, the dimensions of the social demand are multiple, which makes the selection of a coherent set of priorities quite a difficult task. The list of priorities which have been agreed by the ECTP can be gathered in 13 main areas grouped in 3 pillars. [1]

A. Meeting Client/User Requirements

B. Becoming sustainable

C. Transformation of the construction sector.

Innovation is needed to support the growing trend towards integrated construction teams and long-term supply chain collaboration. Although off-site techniques are not applicable in all cases, advanced



manufacturing techniques must be introduced either on- or off-site to enable suppliers and manufacturers to undertake the following: to reduce costs; to enable mass customisation; to reduce installation problems and health and safety risks; to facilitate design; and finally, to improve quality and consistency. The challenge here is to reengineer the construction process, to transform a technology-driven sector, one that is slow to integrate innovation, into a sustainable demand-driven sector, one that is creative, flexible, innovative, knowledge-based, and which offers new business opportunities and attractive work places to all."

Information and Communication Technology is the main innovation driver in most industries and the principle momentum behind economic growth in the 21st century. Process renewal supported by ICT is the main vehicle of ECTP's Vision and SRA. Research priorities are presented in four important areas: processes, products, projects and enterprises. Each of these four areas is divided into two complementary areas of research. This leads to eight main research themes [1].

3.2 Dutch National Level

3.2.1 Introduction

Construction companies in the Netherlands are associated in Bouwend Nederland, which has an active Virtual Design Platform. This platform gives the developments in Dutch construction companies a single denominator and provides them with a joint Plan of Action. All companies operate within the same changing environment. 'If a PPP or other form of integral contract is entered into, it becomes worthwhile to use 3D modelling. 3D modelling can stimulate clear, common work preparations, from design up to execution and even maintenance and/or operation. It should be possible to establish all basic data in the beginning of the project and adhere to them in all of the following stages, with or without controlled changes. A standardised 3D model can provide this. Moreover, a faster and improved cost price overview of the entire project can be obtained at each stage and even one of the whole project life cycle (LCA: life cycle analysis) of the object. In addition, 3D enables an excellent information flow among all construction partners, which makes fixing a contract price less ambiguous and more transparent. 3D applications should give employees a tool to improve the quality of the delivered product. This improvement becomes apparent in, for example, error cost reduction, less ambiguous price offers, better information flow (e.g. blueprints), easier modification implementation, shorter project terms, better dimensioning, more plan of action support, better information services for licences, visualisation, etc. In the preparatory phase, a wide variety of options can be more easily examined and compared more rapidly, 2D drawings can be generated in the execution phase, the as-built phase can be implemented and during operation, the administrator can use the 3D model for facility management, etc. [2].

This is how ICT can be an aid in internal company process optimisation, as well as an aid for chain integration. In order to achieve this, the following is necessary: ICT basics for exchanging messages and information, product-oriented integration and ICT classification system.

3.2.2 The Dutch approach

During a 'case week', various specialists work out a real-life schedule of requirements for a building into a profitable solution. The goal of this case week is to use ICT tools to:

- achieve amazing results;
- learn about using Building Information
- Modelling
- implement new initiatives. [3]

3.3. Dutch Developments at Company Level

The example of Royal BAM Group, one of the leading European construction companies. Royal BAM Group's ICT policy has 5 themes:

1. Reusable budget frameworks, calculating and planning. This enables better insight into the risks and opportunities, increases offer success rates, makes data reusable in subsequent project phases and enables transparent offers to be made.
2. Client interaction and marketing. Clients are given optimal support in the purchase of their home and individual wishes can be taken into account.

3. Integral design makes it possible to quickly give clients insight into alternatives, including the costs and work.
4. Production planning, which reduces error cost and increases safety.
5. Data integration as a basis for the 4 items above.

4. OPPORTUNITIES AND BARRIERS

4.1 Opportunities

General policy needs determine the goals at the European level. They support general economic and social developments. At the Dutch national level, the co-operation between partners in projects plays an important role. For a company such as Royal BAM Group, the main business drivers are: client contacts, making more transparent offers and data continuity throughout a project's lifecycle.

4.2. Barriers

Lack of leadership: the implementation of Virtual Design & Construction solutions requires re-designing processes and investing in employees and means to benefit from working more collaboratively with new technology. Because VDC is a huge development that affects all internal processes, long-term goals and business drivers should be clear and communicated throughout the organisation.

Lack of collaboration: [NON-COST] investments in consistent data need to be re-allocated upfront in the project.

Complexity: the impact of Virtual Design and construction is enormous. Time is required to explore the re-designed processes and new tools.

Poor tools: although tools evolve quickly, many of the applications are not object-oriented.

5. EXPECTATIONS FOR THE NEAR FUTURE

If the number of opportunities for collaboration increases in the near future, chain integration will help optimise many parts of the processes. Clients can expect better and more need-driven information and companies will be able to operate more rapidly and with less error costs.

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BUILDING ERECTION ASSIST SYSTEM APPLIED FOR ACTIVITY CHECKING METHOD

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ABSTRACT

Already, authors provided the method (activity checking method) which does planning validity checking whether the execution of the activity will be possible or not used work data and component data, and construction progress checking used completed wok data. Assist functions of this method are used for construction from planning to progress controlling. In this study, we developed the building erection assist system used activity checking method in order to show the assist function of this method. Also, we cleared that the realization of activity checking method means computerize of planning and progress controlling. The development of actual tool assisting planning and progress controlling of build erection based on this system, is the subject for a future study.

KEYWORDS

Building Erection, Assist Method, Activity Checking Method, Information Technology

1. INTRODUCTION

There are many studies for methods assisting the planning and progress controlling of construction. The assist methods of schedule controlling being a part of planning and progress controlling, are widely used through commercial tools having those assist methods (eg. critical pass method). However, in order to assist whole planning and progress controlling of construction, the assist method using position/shape data of heavy equipments, temporary facilities and components, is also necessary. The field of the study of this paper is the planning and progress controlling assist method which uses building model having position /shape data of components and have automatic planning function or optimization function.

As researches related to whole part of construction planning assist method, there are studies applied for artificial intelligence. Fischer/Aalami[1)] developed the method which automatically generates process model (activity sequence model) used three dimensional building model and work-specimen precedence models.

As researches about work space allocation, there are studies applied for 4-diemnsion (time/space) model. Akinci et al[2)] reported automatic generation of work space volume and duration by simulation used 4-diemnsion product model and work space data. Guo[3)] developed decision assist tool to solve space conflict required temporary work spaces in site plane. This tool uses linking scheduling software. The researches of optimization method related to lift planning continue more than ten years. Zhang et al[4)] studied optimization method of tower cranes planning. Location criteria are balanced workload, minimum likelihood of conflicts with each other, and high efficiency of operations. Experimental results indicate that the computerized model performs satisfactorily. AI-Hussen et al[5)] developed lift planning assist method having optimum algorithm of mobile crane location and specification. This algorithm use geometrics, three dimensional length and lift capacity, and is similar to traditional lift planning heuristics.

A variety of assist methods are proposed as above-mentioned. However, there are no assist methods which are widely used, as method assisting whole planning and progress controlling. The other hand, authors provided activity checking method[6] supporting construction planning. The characteristics of this method are the simple concept and the wide range of the application. The previous paper[6] told the abstract of activity checking method, but did not explain the contents of checking items (checking rules) of activity checking method. This paper shows the contents of checking items (checking rules) through the content of the building erection assist system applied for activity checking method.

2. OBJECT

The purpose of this paper is to show the contents of checking items of activity checking method and verified results of checking items by the system applied for activity checking method. The abstract of activity checking method are showed in chapter 3 and the contents of checking items are showed in chapter 4. The characteristics of activity checking method are cleared by the comparison among the other assist methods in chapter 5.

3. ACTIVITY CHECKING METHOD

3.1 The Definition of Activity Checking

The basic unit of work is activity. The evaluation of activities is necessary when planning and progress controlling is executed. The checking is the evaluation dividing activities two kinds whether success or failure. The checking using computer is possible if checking data and checking rules are set in computer.

In this paper, authors define activity checking as logical matching check among data related to an activity by computer.

The checking whether an activity will be possible to execute or not, is effective in planning work. Also, the checking whether an activity has been done along schedule plan or not, is useful in progress controlling work. The role of activity checking is not substitute of man's brainwork but back-up of man's brainwork.

3.2 Abstract of Activity Checking Method

The concept of activity checking method is as follows. Under the condition that data related to activity is taken in computer, the automatic check of activity execution-possibility and activity in-schedule is possible by checking rules (computer algorithm). Also, the simple automatic setting of a checking condition (a construction parameter) is possible.

The activity checking method is the generic name of checking rules, which are indispensable mechanisms to realize activity checking. Authors call the group of classified checking rules checking item. Table1. shows checking items of activity checking method. In table1., milestone checking is the check comparing activity time (planning and completed) and milestone time. Progress checking is the check comparing an activity's (or a component's) planning time and completed time. The other six checking items are the check of activity execution-possibility. For all checking items, checks are executed about a component or an activity.

4. CONTENTS OF SYSTEM

4.1 Abstract of Development

We developed the building erection assist system for planning and schedule controlling based on the concept of activity checking method. Work specimens dealing with this system are erection work, erection conditioning work, temporary component removed work, bolt fasten work, welding work and ultrasonic examination work. Component specimens dealing with this system are column, beam, auxiliary component (brace etc.), temporary component and conjunction component. The conjunction component is virtual component, and has number of bolts and length of welding in each component. The main development of this system is checking rule's part, and input/output interface part is limited in level to be able to validate checking rule's functions. AutoCAD software was used to display computer screen of building skeleton.

In this system, the stocks checking and structure checking within checking items showed table1. are omitted.

Authors have simulated building erection applied for this system under actual erection schedule. As this simulation result, the checks of each activity and each component about all work specimens of this building erection have succeeded.

4.2 Main Functions

Figure 1 shows the main functions of the system. Rectangular frames of figure1. show mainfunctions and arrows between rectangular framesshow the flow of use. Figure 2. shows the screenof data manipulation and display of the main system functions except for "Erection component model generation" and "Preparatory disposal".

The screen of figure 2. consists of the schedule display part used bar chart, 2,3 dimensional display part of erection component model and detailed data display part of an activity. As the time of activity, working day which is accumulative work day from construction start and calendar day are used.

Table1 Checking Items of Activity Checking Method

Checking item	Function
Milestone checking	Dose the activity time exceed to milestone time?
Progress checking	Comparison of planning time and completed time
Component precedence checking	In component-work start time, are all predecessors of this component-work completed ?
Equipment specification limits checking	Checking the specification limit like a lift capacity of crane
Space interference checking	Space interference checking under set-up/material traveling/works
Activity time checking	Is the duration of work within activity start/end time?
Stocks checking	Checking of the spare amount of temporary facilities stocks
Structure checking	Strength and deformation checking after setting up of components

The functions related activity checking method within the main function of the system are "Activity generation and checking on each work specimen", "Crane data input and erection checking" and "Activity checking for all work specimens, Input/checking of completed work data".

In the stage of activity generation and checking on each work specimen, users primarily generate no component's activities at bar chart display part (fig.2), secondary select components allotted each activity at display part (fig.2) of erection component model. A few checking items are automatically executed in activity generation. If the result of checking is failure, error sign is showed on failed activities of bar chart. The reasons of the failure of the checking are showed at detailed data display part (fig.2) by selecting (click) failed an activity.

In the stage of crane data input and erection checking, users execute data input and checking for erection work and temporary component removed work. The checking items of erection checking are equipment specification limits checking and space interference checking. The failed results of erection checking instantaneously display on computer screen. In the stage of activity checking for all work specimens and input/checking of completed work data, users study planning and progress controlling by progress checking and component precedence checking related to work specimens precedence.

The main functions of the system not to be related directory with activity checking method are "Erection component model generation", "Preparatory disposal" and "Animation of build erection etc. " (in figure1.). For erection component model generation and preparatory disposal, authors used the software modules of erection planning system[6)] . There are two methods generating erection component model. One is manual input used modeler. The other is automatic input from three dimensional CAD data.

In preparatory disposal, there are component weight calculation from component volume, separation of column segment, adding bracket of beam part to column segment, and modification of component weight. In this software module, conjunction components are automatically generated at every conjunction positions.

The function of the animation of building erection is easily realized because activities have both time data and component position/shape data.

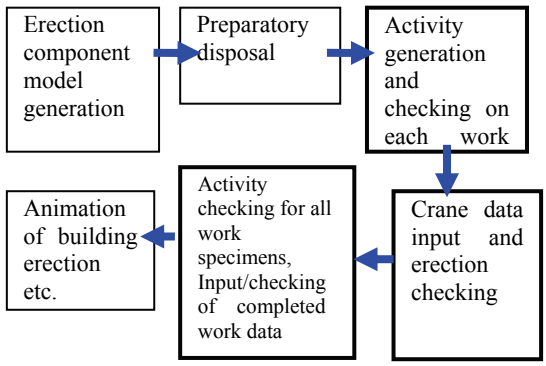


Figure 1 The Main Functions of the System

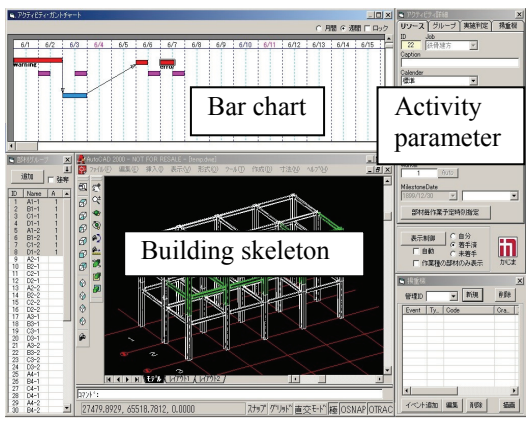


Figure 2 The Screen Display of the Several System Functions

4.3 Contents of Checking Items (Checking Rules)

4.3.1 Component preceding checking

The component preceding checking is success if the checks of all components including the activity could succeed. Component preceding checking on each work specimen judge every component as follows:

(1) About components of the activity, is the work of predecessor work specimen completed?

(2) Are there no problems in construction state of components supporting object's component?

For example of (1) case, the component preceding checking of the activity of ultrasonic examination work do not succeed if the welding works of all components in the activity could not be completed.

For erection work in (2) case, the component preceding checking about all work specimens (or several work specimens) is different from the checking about only erection work specimen. For the example of column erection work, the component preceding checking about all work specimens judges whether the bolt fasten work and welding work of the conjunction components under the column are accomplished. However, in the component preceding checking about only erection work, the check succeeds if the erection work of the bellow column could be completed. Figure3. shows the failed example of the component preceding checking about only erection work.

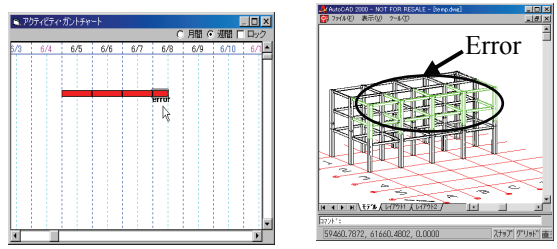


Figure 3 The failed example of component precedence checking

For another example, the component preceding checking of the bolt fasten work and welding work judges whether the erection works of all components linked the conjunction component are accomplished.

4.3.2 Equipment specification limits checking and space interference checking

The equipment specification limits checking and space interference checking are success if the checks of all components including the activity could succeed. The equipment specification limits checking is replaced with crane load-capacity checking because the object of the system is building erection.

The detailed items of crane load-capacity checking are work distance checking and lift capacity checking. The detailed items of space interference checking are lift height checking and contact

checking which calculates whether crane boom contacts built components or not.

The contact checking criteria is the shortest distance between central axis of crane beam and central axis of built components. In the case of the shortest distance less than two meter, contact checking is failure. The value of the contact checking criteria can be modified on computer screen. The crane is located at the position linked to an activity or several activities.

4.3.3 Activity Time Checking

The activity time checking is executed to make a comparison between activity duration time set directly and activity calculation time calculated from amount of work of the activity. The activity time checking succeeds if the activity calculation time could be less than the activity duration time.

Figure 4. shows the success example of activity time checking on the activity generation and checking of erection work. For this example, all erection components in display part (fig.4) are allotted to one day activity, which has 8 hours as activity duration time. The activity calculation time, 5h27m is simultaneously displayed when erection components are allotted to the activity. The error sign is not displayed because the activity calculation time is less than the activity duration time. If the activity calculation time could be more than the activity duration time, the error sign is displayed on the bar chart and the calculation time column on the activity parameter display part is turned to red color.

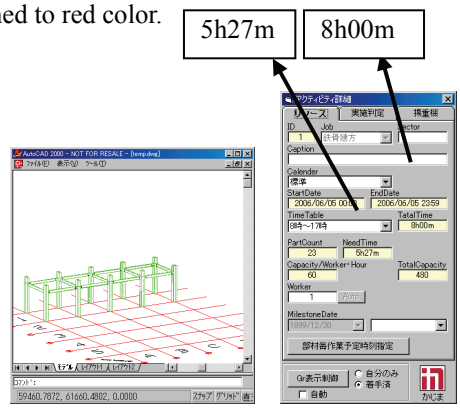


Figure 4 The success example of activity time checking

4.3.4 Milestone checking and progress checking

The milestone checking and progress checking are executed on each activity. Under designating milestone time to arbitrary activity, milestone checking judges to make a comparison between the activity time and the milestone time. The designated conditions of milestone time are finish more early designating time, start more early designating time, finish more late designating time, start more late designating time and so on. The milestone checking is used both planning and progress controlling because activity time has planning time and completed time. (This system has not the function of the progress checking.)

5. DISCUSSION

5.1 The Positioning of Activity Checking Method

As the general methods applying for the assist of planning, there are optimization method and critical path method. Table 2. shows the function of assist methods(the general method adding activity checking method) applying to planning.

From table 2. it is cleared that assist functions of these methods are different. Also, computer models of these methods are different. Therefore, each method is independent of the other methods. For assist functions of construction planning, activity checking method is complementary relation to optimization method and critical path method. Activity checking method is the general planning assist method having assist functions which are different from optimization method and critical path method, and is not only the planning assist method but also the assist method of progress controlling.

5.2 The Significance of Activity Checking Method

By using activity checking method, the bad points of planning and progress controlling work are accurately showed. It is considered that the usefulness of activity checking method will become motivation to promote realizing this method.

The realization of the assist tool combined a variety of assist methods and activity checking method, means the transfer of planning and progress controlling work from paper work to computer work. Activity checking method will be expected to become one of future computer assist methods.

Table 2 The Function of Assist Methods Applying to Planning

Assist method	Function
Activity checking method	Checking of activity execution-possibility and activity obeying construction period limit, Construction parameter can be modified by using checking results
Optimization method	Derivation of solutions to minimize objective variable in objective function
Critical Path Method	Calculation of critical path, Calculation of earliest start/finish time, latest start/finish time and total/free float

6. SUMMARY

The result of this study is that the contents and characteristics of activity checking method are cleared through the development of the building erection assist system applied for this method. For assist functions of construction planning, activity checking method is complementary relation to optimization method and critical path method. The realization of activity checking method means computerize of planning and progress controlling. The development of actual assist tool based on this system is the subject for a future study.

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USER-IN-THE-LOOP: BUILDING TEMPLATES FOR CUSTOMIZED SOCIAL HOUSING *

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ABSTRACT

The objective of this paper is to show how the end user can be involved into the whole building process, specifically in social housing. Therefore, the end users preferences are taken into account in order to increase their satisfaction on the product. The first step consists on obtaining the user preferences by means of an enquiry file (*http://mbserver.uc3m.es/encuesta.htm*). There are about 2.000 surveys fulfilled up today. The results are analyzed in order to classify users into groups with similar features and family composition. Due to the social housing promotion laws, several building templates are produced as a parallel development. The obtained groups are matched with the pre-existing building templates that fit as best as possible with the users' preferences. After this matching, each final user is awarded with the correspondent social dwelling. This is the starting point for the process of the detailed design and configuration of the dwelling by the user. One common web portal enables the use of the design and configuration tools.

KEYWORDS

User Oriented, Social Housing, Building Templates.

1. INTRODUCTION

A long process starts at the very moment any person takes the important decision of buying a dwelling. Usually, purchaser's level of involvement in the process is very low. The user can only take decisions on definite periods and, also, many questions of the process are out of his/her control. Other issue is the degree of relationship between the different stakeholders involved in the process and the end user.

The main goal of this work is to change the actual role played by the user in the construction market. Nowadays, the end user is involved in the process at the beginning, selecting his/here future dwelling and paying it at the end. There are other minor issues, not so important, in which the user is involved. This paper shows one way to change the final user role, placing him into the centre of the process.

The first step is to know the user preferences. The results of an enquiry, which was made between users involved in the buying of social houses in Madrid, are presented here (*http://mbserver.uc3m.es/encuesta.htm*). The results were studied and grouped according to different preference criteria. The aim of the enquiry is to let us know the end user preferences of dwelling. The obtained results can help the developer to offer the user a set of possibilities, buildings and dwellings, according to these groups of preferences.

As it was said previously, this research will be applied in the development and sales process of social houses. Due to the social housing promotion laws, the buildings must be designed previously to the awarding process. The design of the buildings will agree with the results of the enquiry in order to satisfy the highest number of end users. For this

purpose, the features of the buildings are extracted to generate a set of building templates that will aid the matching between user and dwelling.

There is an awarding procedure to select the group of end users among all the possible candidates to obtain a social house. Each selected user must be included in one of the groups obtained in the enquiry. After that, a sub-set of building templates will be presented to each user for choosing among the available options. This sub-set of building templates has to do with the group in which the user was previously included. In this way, there is a higher probability of user's satisfaction.

When the final user has chosen a specific dwelling, the configuration and tuning process begins. Through a web based software tool, the virtual reality visualization of the dwelling is presented to the user who can make some permitted architectural changes and house equipment selection.

2. SCOPE OF THE WORK

2.1. User-in-the-loop

The significant change that this work wants to introduce is the user-in-the-loop philosophy in building construction, from design to the final cycle of life of the building [1]. In this way, the user can take part in all the stages of the process to get a final product according to his/here preferences. Within the actual building market, the user is out of important stages of the construction process and he/she cannot decide about many aspects of his/here future dwelling. This fact implies that the final user's degree of satisfaction about a dwelling depends on the joining between the user desires and the market offer.

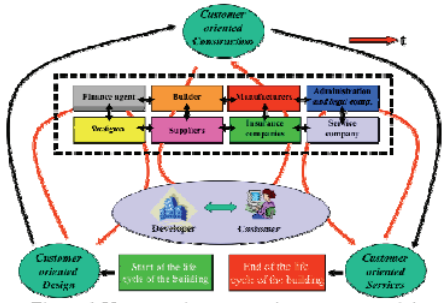


Figure 1 User Centric Construction Process Model

The aim of the research is to find a way of getting the end user involved in the whole process as an active actor. Furthermore, the user must not only be part of the building process but the centre of it (Figure 1). The end user must be able to participate taking decisions and showing some control during the building process. The main purpose is to increase the level of final satisfaction [2].

2.2. Building Templates

So far, the concept of template applied on building was related to 2D drawings or 3D modules. The 2D/3D templates are mainly fixed entities that can be joined in order to obtain a whole building design [3]. Another issue is the level of abstraction of the template. It can be from an empty sketch of a shape to a completely designed module.

For instance, the 2D templates are used to see the dwelling distribution. The layout can be modified by means of different preset options (Figure 2). These kind of templates only give information about one particular dwelling or storey but not about the whole building.

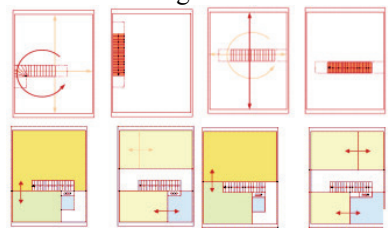


Figure 2 2D Templates

On the other hand, 3D templates can be used to have a scaled final design idea of the building. An example of that is the Bar-Code System where 3D modules are combined to develop an entire building. Housing units are the result of the aggregation of two kinds of space-bars: serving bars (kitchen and bathrooms) and served bars (other functions).

The addition of bars gives rise to a multiplicity of flexible housing layouts, generated by the computer system. Linear blocks are a result of the assemblage of housing units [4].

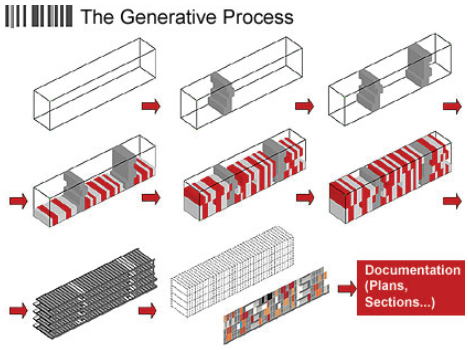


Figure 3 Bar-Code System

The concept used in this research doesn't start from 2D/3D predefined layouts or modules. Building templates are not only a set of designs (3D drawings). At the end of the templates generation process we find the joint of designs with a set of characteristics that make possible the match between building design and user desires.

2.3. Integrated Web Based Tool

Different software tools must be developed to enable and facilitate the use of the system. However, all the tools and the whole system must be usable and user oriented. For this reason, it will be created a common web portal from which all the tools can be accessed in an easy way.

But not only benefits to the end user are pursued. The use of a common platform presents advantages for the ICT development and information sharing among stakeholders. Some of these advantages are:

- All stakeholders have a common tool that enables intercommunication.
- Each stakeholder can have access to a different set of tools, depending on the role in the process.
- Information would be available in whole building life-cycle through access to open tools.
- The use of new standards enables the usability of the information and improves the development phase.
- The tool can be accessed in any place because is web based.
- This feature enables new collaboration business models and services.

3. USER'S PREFERENCES RESEARCH

3.1. Enquiry Development

In this enquiry, it is intended to show not only end user's preferences about social houses developments, in terms of the aspect and location of their dwellings, but to define general groups of personal and familiar profiles. This information will be very valuable in a near future when new developments will be promoted. The enquiry was designed by experts from different work fields in order to ask for the most important and valuable aspects for the user; for example, sociologists, architects, engineers, etc. The enquiry is divided into three main blocks:

1) General Questions

In this block, as described before, questions such as personal and familiar situation are gathered. Examples might be: age, family members, any disabled person in the family, intention to rent or buy…

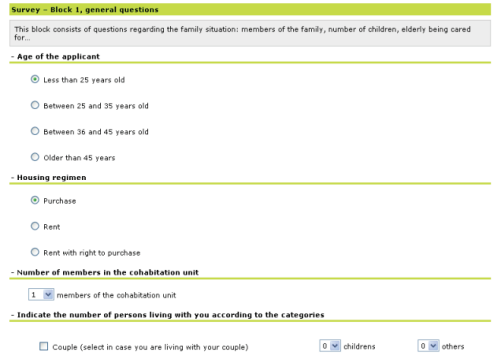


Figure 4 Enquiry's General Questions

2) How would you like your house to look like?

Questions in this block intend to define a framework based on the user preferences for the later design process of the dwelling. We can find here questions related to the house orientation, number of bedrooms, floor selection…

3) The background

Besides obtaining information about the dwellings and the building itself, the end users are able to express their opinion about where they want their

future house to be located; also, they will be able to classify, following a priority order, services surrounding the building: hospitals, schools, church, and so on. All this information can be useful when choosing potential locations for future developments, which will have higher level of acceptance.

The enquiry is available on the following URL: *http://mbserver.uc3m.es/encuesta.htm.* It has a Spanish version and an English one. Due to this, the answers and the results are not restricted to Spain.

3.2. Analysis of Results

There are about 7.500 current visits up to the enquiry web page. A total of 1.925 users have answered the enquiry and the results have been grouped in order to extract the main characteristics to classify future users.

The first important characteristic for considering is to regard the number of components of the user's family. This will define the needed space of the dwelling. It is related to the first block of questions mentioned before. The results show that the most of the users are only one member (36%) or two members (43%).

The second valuable result is derived from the previous one. It is important to know the necessity of space for each number of family members, that is, the number of rooms desired and other living spaces. For the numbers of rooms by number of components some results are:

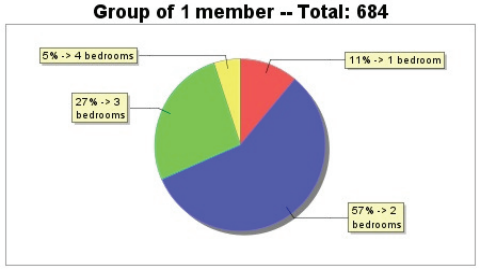


Figure 5 Number of Rooms for One Member Group

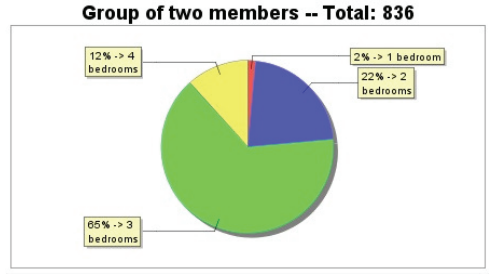


Figure 6 Number of Rooms for Two Members Group

In the two previous graphics, it can be observed that there are two and three rooms dwelling designs are preferred. The families with more than five members are a special case because of the necessity of more rooms, but have not been included in this paper.

Another interesting result is the number of bathrooms and toilets desired. The 91% of the users that answered the enquiry want more than one bathroom or toilet in the dwelling.

Summing up, Figure shows the number of bedrooms independently of the number of family members. The 80% of the users want two or three rooms.

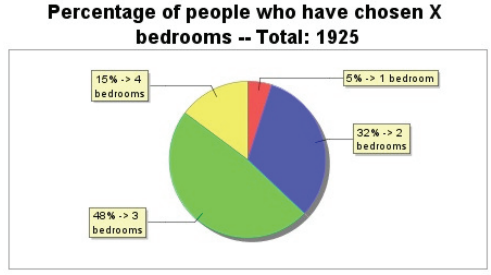


Figure 7 Number of Rooms

With the results of the enquiry showed before some interesting conclusions arise:

- For one and two family components, the ideal dwelling has one more room. That is, two for one member and three for two members.
- For three components, the ideal dwelling has three rooms.
- Selecting more rooms is quite limited by the cost of the dwelling.

- The user that has answered the enquiry is looking for his/here first dwelling. Due to this, the family is formed by one or two members.
- There are two main reasons to want one more room than the number of family members:
  1. The use of the extra space for other necessities.
  2. The future expectative of increasing the family members (i.e. children).
- The preferred number of bathrooms or toilets combinations is two.
- The cost of the dwelling is the most important for the user (social housing).

Other results extracted are related with the surroundings of the dwelling. This information can be useful for developers and urban planners in order to know which services are more important for the users. The answer given by the user must be classified in a 1 to 5 scale.

The results show that people want to live near sanitary services and the living area must have good communication by public transport. On the opposite, people don't give much importance to religious services near their dwelling. One example of these results can be seen on the Figure 8 Public Transport Services.

4. BUILDING TEMPLATES FOR CUSTOMIZED SOCIAL HOUSING

4.1. Dwelling Choice Assisted by Building Templates

As said before, the concept of building templates used in this work differs from a simple 2D or 3D design. The best way to understand what building templates mean here is describing the process showed in the Figure 9.

The process starts when a potential end user wants to buy a dwelling and makes a request for a social house. Then the user must fulfil a questionnaire in order to be classified. This classification helps the developer to offer a set of possible dwelling that can fit into the user preferences.

In the building development process it is necessary to make the 3D design of the building. Moreover, one file must be linked to the 3D model containing a set of rules and dwelling characteristics that enables the user-dwelling matching process in an automatic way.

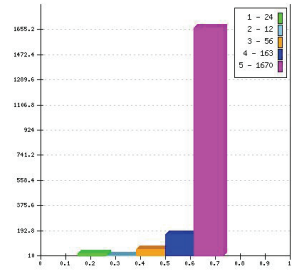


Figure 8 Public Transport Services

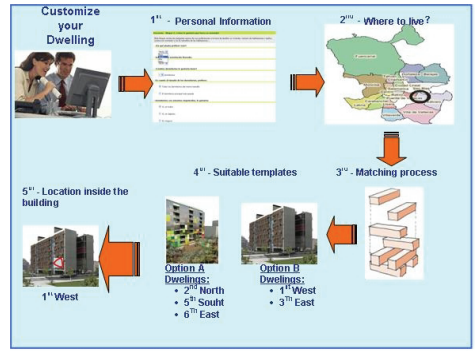


Figure 9 Dwelling Choice Assisted by Building Templates

Supposing that several areas with several developments are available, the user must choose in which one wants to live. The system gives the user some previous information, such as average cost for the square metre of the dwelling in every selected area. If some aspect of the presented information is an impediment for the user, he/she can go back and make another selection.

When the area is selected, a set of possibilities are displayed to the user for making the choice. This set is the building templates. Automatically, the system makes a matching process between user preferences and building characteristics. The result of that operation is a 3D representation of the buildings with the different available dwellings on each one. The user can easily view the future

dwelling and the surroundings. This facilitates the selection.

The virtual representation is very useful for the end user because of two issues. The first is that if the building is already built is not necessary to go to its place to take a look. And the second one is that if the building is in the design stage the user can view the future dwelling before the construction and start a customization process.

4.2. Customization Process

When the user has selected the dwelling, the customization process can start. The user will have a list with the possible allowed modifications (architectural, furniture, decoration, etc.) and he/she will be able to do them according to constraints that the designer put on the 3D building model. For example, the user can move a wall but it cannot be situated a position where there is a window [2].

The customization is an iterative process within a virtual reality based tool. The user can view the result of any modification in real time. Move walls, choose colours, move or change objects… rapid and easily. The tool is connected to the catalogues from suppliers of materials, furniture, etc., offering other possibilities to change to. This will be possible due to the connection of the system with a data base containing the different constructive elements and their suppliers. This data base is called 'intelligent component catalogue'. The cost of changes will be visible at all time in order to enable the end user to make a decision to maintain the configuration or discard the change.

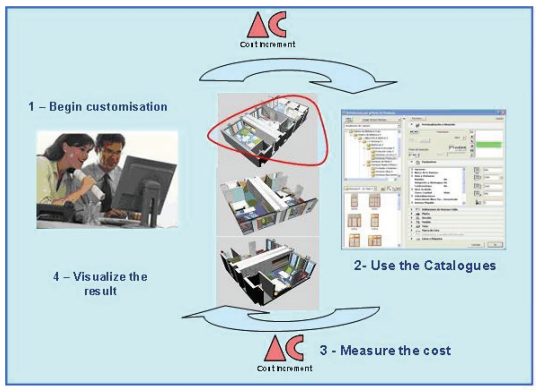


Figure 10 Dwelling Customization Process

5. INTEGRATED WEB PORTAL

The user of the integrated web portal will perceive a single platform, where the different tools are seamlessly integrated, i.e. there is a single common working environment which manages the invocations to different tools/modules.

In general the system should be accessible by all kind of users, regardless their origin, technological skills (the final user of the system must not mandatory be and ICT expert) or language. As a consequence, the platform should provide easy-to-use interfaces. The system must have four main features:

a) Adapted to different user profiles

The platform is not conceived for a specific type of user (e.g. architect). On the contrary, it can be targeted to a wide range of user profiles from the whole AEC/FM industry as manufacturers or builders as the end user. This range of user will be grouped and classified in several user profiles.

The design of the interfaces will also take into account this diversity, being adaptable to the particular requirements for each user profile.

Thus, the following requirements should be met by the system:

- Inclusion of the different actors of the construction process, i.e. architect, builder, manufacturer, etc, with distinction of the functionalities that each of them could access to. This authentication will be controlled with username and password.
- As a result of the above, it is very important that the system is customer-driven, considering the customer as another user profile.

b) Adapted to spatial dispersion

In every construction project the spatial dispersion of actors is very common. Firstly, the number of actors can be big (administration, builders, manufacturers, logistics managers). Secondly the process itself can take place in several scattered locations.

This poses some requirements regarding the integrated portal:

- It should be based on a collaborative environment in such a way that disperse working groups can collaborate efficiently.
- The access to the different tools considered will be remotely accessible, through a web interface.

c) Adapted to geographical diversity

Another quite common characteristic of construction project and also related to the previous one, is the geographical diversity of the projects. The scope of many projects exceeds regional or even national scope. Furthermore, it is more and more common that in the same work site people from multiple origins coincide.

Therefore, the platform should be open take into these particularities of the Construction Sector, especially regarding the following issues:

- It should consider different countries' specificities by providing information or links to common practices and normative documents of the country/region to support the process.
- Iconic interfaces based on standard, international symbols.
- Adaptation of the individual modules (integrated tools) considered will depend on the internal configuration of such modules.

d) Adapted to cultural diversity

Other characteristic of the construction projects is the multiculturalism of people involved in the whole process (customer, architect...). Furthermore, it is more and more common that in the same work site people from multiple origins meet. Due to this, the platform should have:

- Multilingual interfaces should be very convenient. In particular it should be open enough to include in the future any desired new language in the interface, without interfering the functionality
- Iconic interfaces based on standard, international symbols which replace or support textual information would provide openness to the interface.

6. CONCLUSIONS AND FUTURE WORKS

The aim of this work is to increase the customer satisfaction and the participation into the construction business process.

User's preferences have been taken into account by mean of the analysis of the results of an enquiry. Almost 2.000 fulfilled questionnaires have been used from social housing applicants.

On the other hand, the concept of building templates assists to the process of dwelling selection and customization. The fact of designing a specific set of templates goes right against the philosophy of maintaining and open and adaptable system that can be modified according to the changes in the users' wishes or society needs.

The definition of these templates must take into account factors such as architectural, geographical, legal, financial aspects, etc. Templates must accomplish all these issues in different percentages depending on the significance of each one. Moreover, the templates and the user's groups must be established together and not separately.

Another important issue is the fact that user's wishes are something variable, something temporary that evolves with time and with society's alterations. For this reason, a way to capture this continuously changing wishes had to be found in order not to be left behind in the process of fulfilling society's needs.

Furthermore, a process was described so that adaptable, flexible and cost effective designs can be achieved in different parts of the continent. These designs will indeed cover a wide scope of countries and will be able to fulfil end user's requirements as well as presenting the smallest difficulties for installation, operation, maintenance and reparation.

The web portal and its architecture will be developed more in detail and tested. It will be applied to one demonstration scenario to face all possible issues and develop the functionalities.

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PROJECT-BASED KNOWLEDGE MANAGEMENT SYSTEM USING BLOG

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ABSTRACT

Knowledge management (KM), through learning from past projects, has been considered as an effective means for continuous improvement. However, many KM initiatives have failed to meet this expectation, due to the top-down, controlled approach and an ineffective transferring mechanism.

To address this challenging issue, this paper proposes a project-based KM system that helps to acquire and transfer knowledge, using blogs on a project basis instead of knowledge maps. Project blogs store various types of project information and knowledge including communications among project participants, and interconnecting personal blogs of project participants with project blogs would improve collaboration between project participants. Moreover, the proposed KM system could realize "information pulling" of lean construction by delivering prerequisite knowledge of an activity at the time that project participants are ready for that activity. Stored knowledge, with the contextual information extracted from the schedule database, is automatically "pulled" to project participants

KEY WORDS

Knowledge Management, Project-Based, Blogs, Information Pulling

1. INTRODUCTION

The term "Knowledge Management (KM)" is no longer new to the construction organizations. A survey of 170 construction organizations (consultants and contractors) in the United Kingdom shows that about 40% of them already had a KM strategy, and another 41% had plans to develop a strategy in one year (Robinson et al. 2001). As the Korean construction industry is no exception, many Korean construction firms are also trying to institute their own KM system to gain and sustain competitive advantage (Baik 2003).

The KM system (KMS), a system for managing knowledge, is one of the most promising strategic information systems for construction companies. However, current KMSs have not been able to meet engineers' needs on the job site, as those systems have attempted to encompass almost all aspects of construction processes and all types of information, making the systems difficult to use and resulting in a very low frequency of use (Jung et al. 2006). Another survey of UK construction organizations, conducted by Egbu and Botterill (2002), pointed out that general tools in KMS such as Knowledge-based Expert Systems, Communities of Practice, and Decision support systems, ranked low in usage and effectiveness scores among 25 tools for KM, even though conventional IT implementations such as Internet/Intranet and IT-based database ranked high.

The causes of the low usage and ineffectiveness of current KMSs are largely of two types: inherent problems in the system, and managerial problems in the organization. This paper, focusing on the former type, proposes a system that resolves the inherent problems in current KMSs.

2. REALITY OF OPERATING KNOWLEDGE MANAGEMENT SYSTEM IN CONSTRUCTION

In order to identify the reality of operating KMS in construction, we first reviewed the case studies on KM practices in the Korean construction sector and selected three firms, the KMSs of which contain the main features of the KM system functions and architectures that are prevalent in the construction industry.

We conducted case studies by in-depth interviews and observation of users' behavior. The interviews were conducted with the managers of the KM organization of each firm, and enabled us to determine the system architecture of KMS, the KM performance and its problems from the point of view of administrators. The observation of users' behavior was conducted at company headquarters and construction sites. We visited the selected users' workplaces and observed their KM activities, such as inputting knowledge, searching knowledge and reusing knowledge, through the KMSs of their firms. These observations indicated the difficulties that they confronted in each of their KM activities.

2.1 System Architecture of Current Knowledge Management Systems

The systems of all three companies are composed of three functional modules for executing knowledge mapping, knowledge searching and knowledge evaluation, respectively. The knowledge mapping module creates and stores knowledge. In this module, knowledge inputted by employees is stored in its category, which is classified by the relevant working process or the type of knowledge. In the knowledge searching module, a user can search necessary knowledge by inputting relevant keywords into the search engine. The evaluation process module supports knowledge validating and maintenance, as playing an important role in motivating employees to create knowledge by converting knowledge into a quantitative score in their respective evaluations.

Under this architecture, system users register knowledge after selecting its appropriate category, and the applicability and correctness of the knowledge are evaluated by the knowledge master of its category. The evaluated knowledge can be accessed by narrowing down knowledge maps or using the knowledge searching module. Knowledge Evaluation scores are accumulated by unit individuals and teams, and are used for estimating the KM activities of those individuals or teams.

2.2 Problems of Current Knowledge Management Systems

The case studies showed that all of the companies were dissatisfied with the usage and effectiveness of their KM systems. A thorough investigation of the system users' behaviors revealed that the low usage and effectiveness of the current system were mainly due to the following reasons related to capturing, sharing and transferring knowledge.

2.2.1 Capturing

The organization grants incentives to its employees according to the knowledge activities score of individuals and teams, or compels its employees to meet a minimum knowledge activities score. Although the purpose of such policies is to increase the quantity of knowledge, those policies increase only perfunctory knowledge creation, which causes deterioration in knowledge quality. The deteriorated knowledge quality reduces users' satisfaction, and accordingly usage of the system. Moreover, incentives or compulsions make employees consider knowledge activities as entailing an additional significant workload. As a result, employees come to be reluctant to use KMS. Therefore, it can be inferred that a controlled and top-down system approach hinders voluntary knowledge activities within the organization.

2.2.2 Storing

Knowledge that users acquire from the system includes only limited information on knowledge context. The contextual information provided in the system is limited to the name of the creator, the department and the created time. However, in order to effectively apply certain knowledge to the

project, detailed situational information of the project is needed, such as a project description, the associated activity, the involved companies as well as the relevant knowledge that was created earlier. In order both to fully understand the knowledge and to engender confidence in the credibility of the knowledge, what is also required is detailed information from the knowledge creator, such as his or her work experience, skills, and the knowledge description level. This knowledge-contextual information certainly exists at the time of creation, but tends to be lost in the process of storing knowledge.

2.2.3 Transferring

The system includes two manual knowledge transfer methods: searching, and narrowing down knowledge maps. Both methods are efficient from the standpoint of system resources, because knowledge is delivered on the user's demand. However, they are inefficient in that the users' time and effort are required. Moreover, this inefficiency is the main reason that employees choose other, simpler KM techniques such as telephoning and face-to-face meetings, despite their high recognition of the quantity and quality of the knowledge available in the KM system. Moreover, those other, simpler methods serve to keep users in a state of low recognition of their knowledge needs.

3. PROJECT-BASED APPROACH TO KNOWLEDGE MANAGEMENT

In order to address these challenging issues, a project-based KMS is suggested. Whereas the conventional KMS focuses on organizational knowledge, handling KM processes on the basis of each department of the organization, the proposed new system focuses on project knowledge, entailing the execution of all of the KM processes on the basis of each project. All of the knowledge created during the project is stored in a project-specific knowledge repository along with project information, and this enables the automatic transfer of requisite knowledge to participants of other projects based on project-contextual information. This project-based approach entails three implementation mechanisms, each of which overcomes impediments to KM processes in the conventional KMS.

3.1 Adapting Blogs

'Blogs' are user-generated websites that display journal-style entries in a reverse chronological order (Blog 2007). They are easily set up, maintained and contributed to by a broad network of loosely associated individuals. Blogs were originally used as private media, but recently they have been recognized as powerful KM tools by practitioners who have observed the enormous knowledge that blogs have produced and the expansive social networks that they interconnect. Blog-adapted practices have already been introduced in other industries. For instance, IBM allows its employees in 30 global branches to discuss software development process and business strategies in their blogs (Lee et al. 2005).

Adapting blogs to construction KM has already been addressed conceptually by Mills (2006). First, he identifies that construction is essentially a people-focused enterprise that engages formal and informal networks that must share knowledge in order to succeed. This people-centered aspect of knowledge sharing in the construction industry is also addressed by Cleveland (1999) and Chinowsky and Molenaar (2005). Second, Mills argues that blogs, as people-centric tools entailing user-driven social networks, represent a democratic, bottom-up approach to KM implementation in construction that helps to remove obstacles caused mainly by rigidly controlled, top-down approaches.

The project-based approach adapts blogs to a personal knowledge repository as well as a project-knowledge repository. The impediment in the capturing process of the conventional approach would mostly be solved by the adaptation of blogs, which encourage voluntary knowledge creation. As a result, we expect that the open and democratic aspects of blogs would change the conventional approach's loop effect, which controls all KM activities by incentives and compulsion.

3.2 Contextual Knowledge Management

Context is defined as the aggregate relevant conditions and surrounding influences that make a situation unique and comprehensible (Anderson, 1995). According to Goldkuhl and Braf (2000), contextual knowledge encompasses the

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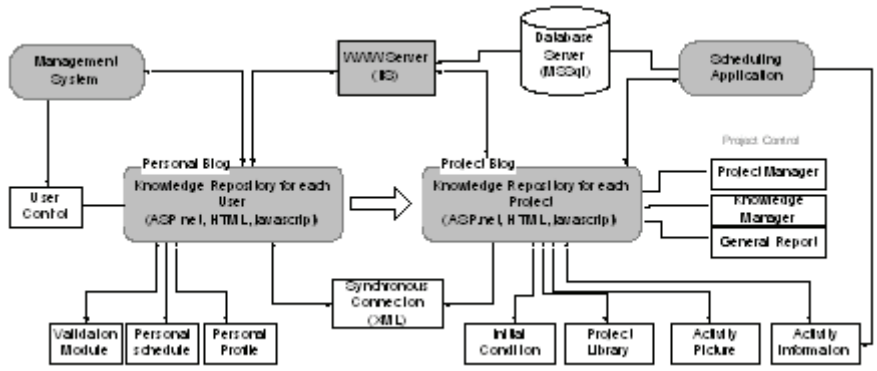


Figure 1 Contextual Knowledge Management System Architecture

organizational situations in which knowledge is created, transferred and utilized, and enables people to reuse knowledge by allowing them to apply knowledge from a similar or analogous past situation to a current situation. .He argues that contextual knowledge is mainly composed of both situational knowledge, which is derived from actual situations as well as earlier knowledge concerning similar situations, and trans-situational knowledge, which can be generalized knowledge abstracted from earlier situations and particular experiences (memories) from those earlier situations. In regard to construction knowledge, situational knowledge could be considered to be the environment and situational information of the project, and trans-situational knowledge could be considered to be the project participants' experiences and knowledge from earlier projects as well as their understanding of the specific knowledge. Only when such contextual knowledge is provided can specific knowledge from a particular situation be reused. Moreover, a reuser's understanding of specific knowledge can be improved.

In order to provide this contextual knowledge in construction, we present a blog-adapted system architecture (Figure 1). As shown in Figure 1, a personal blog, as a knowledge repository for each user, plays a role in delivering trans-situational knowledge. Trans-situational knowledge could be captured in rich personal information representing a blog creator's whole career and skills, and could also be acquired from a blog creator's awareness of certain specific knowledge, which is reflected in his or her earlier knowledge as well as others' evaluation of and comments on that knowledge. A project blog, a knowledge repository for each project, plays a role in delivering situational knowledge. In order to deliver situational knowledge, activity-related knowledge is associated with its activity information so that when it is delivered, detailed information on related activities such as the activity description, start date, completion date, and companies involved, as well as detailed project information such as the location, type of project, duration and type of contract, can be delivered together.

A project blog would also perform functions as project-specific web sites, forums for collaboration among project participants. It could store various types of project-related information with schedule information, and so it could also provide information and knowledge relevant to a specific activity. Moreover, using trackback or comments, it could capture live communication among participants about specific knowledge.

3.3 Information Pulling

Thorpe and Mead (2001) define the pull model of information as delivering "just-in-time" information characterized by in-phase timing, low volume, user-selected data, and a project focus, whereas the traditional push model handles just-in-case information characterized by out-of-phase timing, high volume, irrelevant data, and an organizational focus. On this basis, we define "information pulling" as delivering prerequisite knowledge of the successor activity at the time that project participants are ready for that activity. The

key purpose in "information pulling" is to make the information system know when to deliver prerequisite knowledge for a succeeding activity.

In information pulling, the proposed system utilizes knowledge context to determine the time of and prerequisite knowledge for each activity. Activity is the key component of knowledge context. From the project scheduling application, we can extract activity information. Activity WBS, CBS, and OBS information impart the characteristics of work information to the knowledge context. In the knowledge context, a personal profile is also important in categorizing users who receive knowledge. Keywords extracted from inputted knowledge are also stored in the knowledge context. This knowledge context is then stored with the knowledge in the database.

Such accumulated knowledge, with activity contextual information extracted from the project scheduling application, is automatically delivered to other users facing a similar activity in a new project. The delivery process is performed in the following four steps: (1) the system notes, from the database of the project scheduling application, the fact that the start date of the successor activity is close at hand; (2) the context of the successor activity is extracted from the project scheduling application, and then the knowledge context is created; (3) knowledge from similar activities in finished projects is searched from knowledge databases, using the knowledge context created in the previous step; (4) extracted knowledge is transferred to a user by e-mail. This flow of storing and delivering knowledge in information pulling is illustrated in Figure 2.

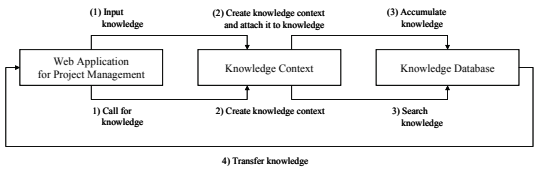


Figure 2: Flow of Knowledge Storage and Knowledge Delivery in Information Pulling

4. CONCEPTUAL MODEL FOR INDUSTRY-WIDE SHARING

In order to facilitate knowledge sharing in small-to-medium enterprises (SMEs), we propose a web portal to extend the project-based KM system. Through this portal, the functions of the project-based KMS are provided to SMEs using ASP. Because insufficient funding is the most critical obstacle to implementing KM in SMEs, and as ASP is the lowest-cost option among KMS strategies, using ASP could encourage SMEs to implement KM. In addition, individual engineers can also participate in knowledge sharing by creating a personal blog in the portal.

The main purpose of this portal is to broaden SMEs' knowledge-sharing networks by facilitating knowledge sharing between SMEs, thereby enhancing the limited scope of SMEs' knowledge-sharing networks. For this purpose, each SME needs to allow some knowledge stored in the project-based KMS to be shared with other participating SMEs. When the project is initiated, managers set up a critical process and knowledge mapping. Participants in each project have their own blogs that are used as personal and project-knowledge repositories. Individual users should sign on to this portal and keep personal blogs, like SME members, and are given access to the open-to-the-public knowledge database. Users can find the knowledge they need at any time through a knowledge search.

These knowledge-sharing networks among SMEs would be very effective in disseminating best practices. If a finished project is evaluated as a best practice, just allowing the project blog of a best practice to be accessible to other SMEs in the portal could provide live knowledge and vivid recordings of the project. As mentioned above, a project blog could capture even the communication between project participants so that not only the outline and result of the best practice, but also more in-depth insight into the best practice could be provided to members through the portal.

5. CONCLUSIONS

We determined, from the results of in-depth case studies of practices within the Korean construction sector, that the main causes of the low usage and effectiveness of conventional KMS are inherent in each of the existing KM processes. In the knowledge-capturing process, the controlled and top-down approach of the system hinders voluntary knowledge creation in the organization, the result being that knowledge context is left out of the knowledge-storing process. Additionally,

the knowledge-transfer process relies entirely on manual methods that can provide information only in response to users' demands.

The proposed project-based KMS uses blogs as a knowledge repository tool for individuals and projects in order to exploit the blogs' advantages in motivating knowledge creation. When knowledge is delivered, this system simultaneously provides rich contextual knowledge from the project and personal blogs together, which enhances the understanding of the knowledge and provides a basis of decision-making in the reusability of the knowledge of a particular situation. Moreover, this system realizes "information pulling", which entails the automatic delivery of prerequisite knowledge for a succeeding activity, using the contextual information extracted from the project scheduling application. This system is expected to facilitate the increased reuse of appropriate knowledge and the strengthening of the positive feedback loop of KM, through motivating more users to use the system as voluntary creators of knowledge.

Furthermore, the conceptual model of the portal was introduced in order to extend this approach to SMEs and facilitate their knowledge sharing. Indeed, SMEs can expand their knowledge sharing and transferring by using the portal's ASP.

6. ACKNOWLEDGMENTS

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SYNCHRONOUS DESIGN COLLABORATION IN A PEER-TO-PEER NETWORK

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ABSTRACT

The Internet has revolutionized the way software systems work. Many applications, such as online games and instant messengers, have utilized web-related technologies to cooperate over the Internet. Recently, some researchers have utilized web-related technologies in Computer–Aided Design to allow real-time collaboration between users over the web. All these systems are based on the client-server model. In this kind of collaborative design environment, the system grouping, operation and communication all have to rely on the central server. In order to improve accessibility and flexibility in collaborative design and to provide a more load-balanced and extensible environment, this paper presents a prototype implementation of collaborative design tools based on a Peer-to-peer (P2P) model. The users can conveniently form design groups, by connecting directly to each other, anytime and anywhere, without the presence of a central server. All peers are equal in functionalities and computing loads. Based on the P2P network model, several mechanisms are proposed in this paper to form a working model of this system. Then, the object model design and implementation of this P2P system is presented.

KEYWORDS

Computer-Aided Design, Internet, Synchronous Collaboration, Distributed Processing, Peer-to-Peer

1. INTRODUCTION

Computer-aided design (CAD) system is one of the most widely-used computing systems in the Architecture/Engineering/Construction industry for various types of design projects. Architects, structural engineers, and construction engineers, etc. all rely on CAD systems for generating discipline-specific designs on computer-based digital drawings or visual models, such as 3-dimensional (3D) virtual reality models by architects, finite element analytical models by structural engineers, and construction drawings by construction engineers. Two types of collaborations generally occur during the design process. They are collaborations between multi-disciplinary design teams, such as the collaboration between structural engineers, architects and construction engineers, and collaborations within a specific disciplinary design team, such as the collaboration between architects who work on the same architectural design project. The characteristic of collaboration between multi-disciplinary design teams is more asynchronous. Except for discussing a preliminary design plan in the initial stage of a design, multi-disciplinary collaborations are a process in which a design team performs all its tasks and then hands the results off to the next design team. On the contrary, the characteristic of collaboration between members of the same design team is more synchronous. The task of each member is part of a

design in a specific discipline and can be performed concurrently. During the collaboration process, team members work on their parts and communicate frequently to check the overall progress and have their tasks integrated.

Using CAD systems for complex drawing or rigorous 3D model design usually is time-consuming and labor-intensive work. For large-scale design projects, organizing a design team to share the work and cooperate concurrently can speed up the process if the communication between designers and the integration of separated jobs can be well handled. The Internet is the perfect media for group communication and data integration. A collaborative design environment, adopting Information Technology to enable direct communication and data exchange over the Internet between geographically distributed CAD systems, is expected to greatly improve efficiency and convenience for the design group. By using today's information technology, it is possible to build a synchronous collaborative design system to support the above collaboration requirements by allowing users to work together in the same virtual design space to view the progress of each other's work in real-time and cooperate with each other via various synchronous communication tools. Such a distributed system should provide the most instant and effective support for synchronous collaborations.

Some researchers have utilized information technology to support asynchronous collaborative design works. For example, Fruchter [1] developed an Internet-based environment to support multi-disciplinary, geographically distributed A/E/C teamwork through shared graphics. On the other hand, Some researchers have utilized web-related technologies in Computer–Aided Design to allow real-time collaboration between users over the web. Abdel-Wahab et al. [2] established a UNIX-based collaborative environment using Internet and UNIX interprocess communication. Mitchell [3] pointed out that industrial development and academic research have significantly advanced the technology available for network-enabled CAD applications. Recent system developments include Nam and Wright [4] and Tay and Roy [5]. All these systems successfully showed that geographically distributed users can share data and work together to build and edit visualized models using the Internet.

All the above synchronous and asynchronous collaborative design systems are based on the client-server model. In this kind of distributed system, the system grouping, operation and communication all rely on the central server. The peer-to-peer (P2P) model has emerged as an alternative to the client-server model for distributed systems. In a P2P network model, each node has both client and server functionally. That means a node can connect to and be connected to by other nodes. In addition, all nodes usually are executing the same program and exploiting the same functions, thus are called peers. Comparing these two network models, the P2P model has the potential to provide more efficient communication, to be more crash-proof, and to take advantage of idle computing capacity; whereas, the client-server model has the potential to provide more secure and more easily managed information as well as not requiring unnecessary duplication of information.

Considering the synchronous collaborative design scenario, in which each designer is equally assigned part of the design tasks and works concurrently, and design data and information exchange in real-time is a requirement. Using the client-server model for real-time online collaborative design systems can also achieve synchronous collaboration by enabling frequent automatic updates between server and clients. However, its drawbacks are that computing loads are concentrated on the server and the availability of the server is critical. In addition, the rigorous reliance on the central server makes the forming of design groups somewhat inconvenient and inflexible, and any fault on the server will disrupt the whole group.

For synchronous design collaborations, the computational loads would be better distributed to each designer's machine, not concentrated on the central server. In addition, the reliance on a central server would be better relieved. Thus, the P2P model has advantages from a system operation viewpoint. Using the P2P model for synchronous design collaboration, all peers are equal in functionalities, computing loads, and communication loads. In addition, the elimination of the central server in the P2P model introduces

benefits from system usage viewpoint. The users can conveniently form design groups any time and anywhere using their Internet-connected machines just by connecting directly to each other without requesting the presence of the central server. The issues in the client-server model such as the availability of the central server and distance to the central server (bandwidth between clients and server) no longer exist. Thus, its mobility and convenience in forming and maintaining a design team is truly incomparable to using the client server model. Based on the characteristics of synchronous collaboration, using a P2P model may not be necessary, but it is more suitable from system operation and system usage viewpoints.

For improved serviceability, load-balancing and performance of the current client-server based synchronous collaborative design systems, this paper presents a new real-time online collaborative computer-aided design system named ROCCAD based on the P2P network model. The data is communicated on an overlay network formed by a set of unicast (one-to-one) connections between peers. The connection rule is a peer can connect to at most one peer and be connected to by many peers, thus the resulting network is a tree network (Tree First). This Tree First P2P based overlay network is built totally on the application level since it is based on standard Internet protocols and network equipment. It is highly extensible since all the communications are handled by the application program.

2. SYSTEM REQUIREMENTS

From a system development perspective, some requirements are crucial for successfully permitting P2P-based real-time online collaboration for computer-aided design. Discussion of these requirements follows with some solutions provided.

2.1 Communication Efficiency

The real-time collaborative design process involves frequent communications over the Internet among peers. The efficiency of Internet communication is the key to system success. In order to permit every user to view all the users' progresses on a synchronized viewport and communicate with others in real-time through interfaces, the most common communication in the proposed environment is each peer updates its state to the other peers. The characteristic of this communication is an identical update message to all the other peers. Therefore, multicast (one-to-many) technology can be adopted to improve the efficiency in communication. The proposed system adopts the Application Level Multicast (ALM) scheme. ALM is message broadcasting handled by the program at the application level. The application has to be programmed to deal with message passing. The efficiency is improved by activating a message receiver as a new message sender immediately after completing the receiving.

2.2 Data Synchronization

The collaborative design system needs to maintain and manage design data created by multiple users in a distributed environment. In addition, each peer must have the ability to communicate directly with the other peers over the Internet. Besides the low-level TCP/IP protocol, another high-level mutual protocol on the string messages for message identification and processing is necessary.

In the proposed system, the design data is stored and communicated in the same format, which is a string started by a keyword specifying its type and followed by its individual attributes. For recognition and processing of data in a distributed environment, a common protocol among peers is established by system rule which reserves a keyword and specifies a set of attributes for each type of data. On the other hand, each datum must have a unique ID to be distinguished in the distributed environment. The proposed data labeling scheme to ID design data is its creator's ID plus a serial number, and the ID of a user is the IP address of the user's machine following by the connecting port. This scheme can ensure all the resulting IDs in a distributed environment are identical.

In order to achieve data synchronization so that every user can consistently view the shared model, which is constantly updated by all users in real-time, each peer has to notify all the other peers by broadcasting its modification, such as addition, deleting, scaling, or moving a modeling object, to the model immediately after an action is completed and confirmed. As a result, all peers in a group have the same data all the time to achieve data

consistency and synchronization. In addition, any newly joined or rejoined peer must clear its data and then download all the current design data from the peer with which it connects to ensure data consistency.

2.3 System Working Model

A set of distributed mechanisms is required to form the system working model of the proposed distributed system for each peer to thoroughly handle all the possible issues and scenarios, such as the joining and leaving of a user, access and request conflicts, data transmission, data consistency and synchronization, etc.

The proposed on-line process begins with a peer sending a request to the root peer before joining or leaving the group. Upon receiving the request, the root peer will update its group list by requesting all the other peers to send their information to it, including the newly joined peer. After the root has updated its group list, the list is broadcast to all the other peers and replaces the old list to complete the list update of the group. After the new peer joins and the group lists of all the peers are updated, the new peer can obtain the current design data by simply downloading all the design data from the peer which it connects to. This mechanism is robust and the resulting group lists are in the same order on all peers.

When a peer leaves the design group, other peers must not be affected by its leaving. To achieve this, the Internet connections of those peers connected to a leaving peer must be recovered to reconnect with some other peers in order to keep those peers in the group. A recovering peer will first try to reconnect to the peer which the leaving peer was connected to. If such a peer does not exist, this means the leaving peer is the root. In this case, the peer ordered first in the leaving peers becomes the new root of the design group and the other leaving peers connect to it to recover their connections.

In a collaborative design environment, all the design component objects are openly shared and accessible by all users. To avoid an object being manipulated by more than one user, a lock-based mechanism for object access is necessary. If a user wants to manipulate an object, he or she must request a lock on the object first. After the lock is granted, the requesting user becomes the owner of the object and can modify it. To ensure a lock on an object will not be granted to more than one user, a locked object cannot be requested until its owner releases its lock. To ensure all the locked objects belong to an owner, a peer automatically releases all its locks on objects immediately before leaving the group.

The proposed lock-based mechanism for P2P network begins by broadcasting the locking request from the requesting peer to all the other peers. Upon receiving the request, each peer simple tries to lock the object for the requesting peer. No matter if the locking is successful or not, no confirming or failure message is sent back to the requesting peer for efficiency. Therefore, both locking and unlocking are done after a broadcast request in this mechanism. Although most of the locking requests can be done efficiently in this way, a requesting conflict is possible if another user requests a lock on the same object while a locking request on it is still transmitting and not completed yet. This conflict occurs when any peer who receives multiple locking requests or if the requesting peer receives requests on the same object. To resolve this conflict, the locks of the object from all peers must be released. Because only the owner peer has the right to unlock its objects, the proposed solution is a requesting peer automatically broadcasts an unlocking message to all peers to cancel the locks of those peers which have received its locking request whenever it receives another locking request on the same object which it is requesting.

In order to maintain data consistency and synchronization among all peers, each peer must update its state to the other peers by broadcasting an update message frequently. To broadcast an update of a peer, each peer forwards a received message upward or downward to its connecting peers which have not received the message yet by following the tree network structure. Since all peers have to send their own updates and forward the updates received from connecting peers concurrently, it is very difficult to schedule these communications through a single port. A feasible solution is every peer has to create multiple connections through different ports for each of its connecting peers to form an overlay network and handle the communications with all its connecting peers concurrently. The multi-thread capability

included in Java can be used to fulfill this goal by creating multiple threads to run concurrently and each thread has a connection to another peer.

In addition to a data transmission mechanism, a set of update frequencies is necessary for each kind of message to determine how often a peer should broadcast its various updates. The update frequency of the design data is a peer sends out its update whenever the user adds an object, deletes an object, or releases the lock on an object. The update frequency of the message board is a peer sends out its update whenever the user hits the "enter" key. The update frequency of the whiteboard is a peer sends out its update whenever the user draws a new line.

2.4 User Interface

A 3D design environment with interactive and graphical user interface to support CAD operations is the basic requirement for modern computer-aided design systems, and also is basic for the proposed collaborative design system. Therefore, a viewport, for each peer, for synchronously displaying the whole 3D design project worked on by the design team in the shared virtual design space is necessary. The current design model should be visually displayed as 3D graphics in the viewport using a 3D graphics library. In addition to the graphical interface for displaying the shared design project synchronously, communication interfaces can further facilitate cooperation by allowing users to communicate in real-time through the system directly. Therefore, the proposed system should provide a message board and a whiteboard for Internet conferencing.

3. IMPLEMENTATION

The proposed prototype system can be thought of as the fusion of a CAD program and a messenger program. Considering the functionalities of these two programs, the proposed system architecture is a three-tier system. The object model of the proposed prototype system (ROCCAD) is shown in Figure 1.

The first component is the CAD System which provides CAD functionalities and an interface to aid the user to do the design and synchronously view the progress of the collaborative design project worked on by multiple users in real-time.

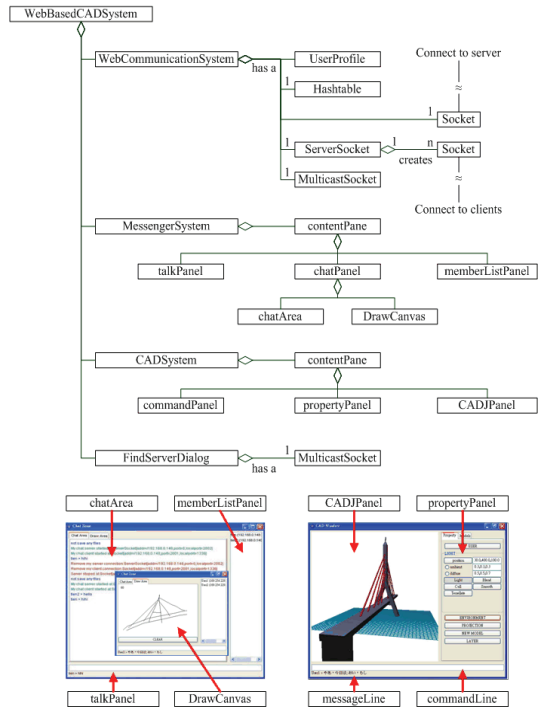


Figure 1 The object model of the proposed prototype system (ROCCAD)

The second component is the MessengerSystem which provides messenger functionalities and interfaces to allow the user to do Internet conferencing with the other peers. The third component is the Web Communication System which provides functionalities to allow the proposed system to connect and communicate with each peer over the Internet.

4. CONCLUSIONS

This paper has presented a prototype system, named ROCCAD, for real-time online collaborative computer-aided design. A key feature of the proposed system is to provide mutual graphic or drawing interchanges in real-time during a design development process for synchronous design collaboration. Compared with the current client-server based collaborative design systems, the features of this system are that online collaboration is based on a P2P network for improving the convenience and flexibility of system usage, and the communication is based on the ALM scheme for improving efficiency. After

taking into consideration various aspects of implementing this P2P based system, the system requirements have been addressed. To fulfill these system requirements, a set of mechanisms has been proposed to form the system working model of the system. Then the object model design and implementation of ROCCAD have been presented.

Considering the real-time collaborative design scenario, its characteristic is all designers in a design team are equal in duties, loadings and functionalities, which is quite similar to the characteristic of all peers in a P2P network. Therefore, using a P2P network is more natural and load-balanced for real-time collaborative design. In addition, the P2P model has several advantages from a user's view point in comparison with the client-server model for collaborative design. First, it is more convenient since the users can form a design group by connecting directly to each other anytime and anywhere without the presence of a central server. Second, it is more flexible because any peer is allowed to join or leave the network during the design process without limitation. Third, it is more robust because the malfunction of any peer will not affect the other peers as well as the whole design project. Fourth, it is more extensible because of the decentralized network and the ALM scheme. Although the system working model in a P2P network is somewhat complex, it has been proved that the proposed mechanisms can conquer the complexities and achieve the same functionalities for supporting real-time collaborative design as using the client-server model.

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USE OF WEB TECHNOLOGIES FOR RAISING AWARENESS ABOUT SEISMIC RISK

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ABSTRACT

Earthquake problems are not new to our country. We have witnessed several moderate earthquakes in last 2 decades causing innumerable property loss and life loss. In order to minimize the losses, we need to raise the awareness about earthquake resistant design of structures. This can be achieved by spreading the information on hazard, vulnerability and risk to concerned people.

Damage caused by a seismic event depends, to a large extent, on the a priori availability of information related to estimated hazard and vulnerability and their use in proper planning and construction. With the emergence of new web technologies such as Google Maps, Ruby on Rails and AJAX, systems which are robust in harnessing the collective information can be developed. In this paper, we discuss the quantification of risk of any location using these technologies.

KEYWORDS

Ruby on Rails, Google Map, Ajax

1. INTRODUCTION

No matter how quiet India appears in terms of seismic events, statistically last 2 decades were the most disastrous decades in terms of damage and loses caused by various seismic events. In just 5 years since 2001 the Andaman-Sumatra earthquake and Kashmir earthquakes have doubled the 100,000 people who were killed by earthquakes in the Indian region in the previous past 2 centuries.[1] Moreover many of these events like Uttarkashi earthquake (M6.6, 1991), Latur – Osmanabad earthquake (M6.3, 1993), Jabalpur earthquake (M6.0, 1997), Chamoli earthquake (M6.8, 1999), Bhuj earthquake (M6.9, 2001) and Kashmir earthquake (M7.0, 2005) were of moderate to strong severity but the loss and damage caused by them were far beyond expected. The root cause for above mentioned earthquake disasters are lack of awareness about earthquakes and earthquake disasters, among general public in addition with lack of seismic risk information at the time of structural design. The basic aim of this application is to eliminate above mentioned fallacy by providing general public and professionals with adequate information on seismic risk.

On the other hand a joint research by the Internet and Mobile Association of India (IAMAI) and (IMRB) International suggests a significant rise in the number of Internet users in India - an increase from 33 million in March 2006 to 37 million in September 2006. It also suggests an increase in the number of active users from 21.1 Million in March 2006 to 25 Million in September 2006. Active Users are the users who have used the internet at least one in the last 30 days. It was also estimated that the Internet User base is likely to cross the 40 million mark by March 2007, with user base is likely to be 42 Million and the Active User base is

likely to be 28 Million. These statistics indicates rapid growth of internet users in India [2].This application was developed with a vision of making an interactive system for disseminating crucial information like regional seismic risk to a large number of people through an easily accessible mode. And World Wide Web (WWW) was chosen as the most suitable platform for fulfilling our requirements of disseminating information instantly to large number of people.

2. RISK EVALUATION

Seismic Risk of an area is defined as the expected extent of damage to a property and loss of life at the time of a seismic event [3]. Thus seismic risk evaluation will be extremely useful in undertaking long-term mitigation and preparedness measures against seismic disasters. Risk assessment, on the other hand, requires data related to hazard, vulnerability, exposure time and economic activities. Thus, to fulfill these requirements thorough studies need to be undertaken to collect data and knowledge required for undertaking risk assessment and to utilize the power of IT in order to develop more interactive applications in the field of risk assessment. Seismic risk pertaining to any region depends upon 3 major components i.e. seismic hazard, seismic vulnerability and exposure time. Seismic hazard is defined in terms of ground motion parameter like Peak Ground Acceleration (PGA). According to IS 1893:2002, Indian subcontinent has been divided into 4 seismic zones based upon the expected PGA value in a particular region. This zonation based PGA has been used to represent the effects of seismic hazard in this application. Seismic Vulnerability on the other hand is defined as the degree of damage that is expected to occur depending on the type of structure in an area. Thus Earthquake Risk is the product of the hazard intensity and the vulnerability of buildings and the output of a seismic risk analysis could give the probability of damage and loss from nearby earthquake and its quantification requires socio economic and housing statistics [4].

3. APPLICATION DEVELOPMENT

This application was developed using Ruby on Rails (RoR), a full-stack framework for developing database-backed web applications according to the Model-View-Control (MVC) pattern [5]. The MVC pattern is important because of its power of separating the data from the user interface. All the modules related to data goes into the model classes. All related to data - controlling functions goes into the controller class and the user interface module goes into the view class. This kind of architecture is useful in case of problems involving large amount of data with an acceptable variation with time as it separates both the functionalities from each other. Since the data pertaining to seismic risk evaluation involves large number of earthquake records with considerable randomness, Ruby on Rails became the best choice for developing this application. This separation of view from model and controller class also made mashing up of Google maps more easy and flexible. The overall process of application development can be classified into 3 categories:

1. Data collection and Model generation
2. Creating Controllers
3. View or HTML sheets design.

3.1 Data Collection and Model Generation

Data used in this application was a collective form of different input parameters required to compute seismic hazard and vulnerability. Hazard was estimated in terms of seismic zonation and corresponding peak ground acceleration (PGA).While vulnerability was defined in terms of type of structures and their risk for different seismic intensities.

3.1.1 Seismic Hazard Estimation

According to IS 1893: 2002 India has been classified into 4 seismic zones. These zones are different in terms of peak ground acceleration (PGA) values that are fixed for them as shown in Table 1[6]. Hazard Severity is classified different for different regions based upon these PGA values or zones. For the risk evaluation in our application we have classified the severities for different seismic zones as follows:

Table 1 Seismic Zones &Corresponding Hazard Severity

Seismic Zone	Peak Ground Acceleration (PGA)	Hazard Severity
II	0.1	Low (L)
III	0.16	Moderate (M)
IV	0.24	High (H)
V	0.36	Very High (VH)

3.1.2 Seismic Vulnerability Estimation

Vulnerability Severity Index for this application was taken from Vulnerability Atlas Map of India. This atlas was prepared by Building Materials and Technology Promotional Council (BMTPC) and the vulnerability severity is classified on the basis different types of structures under different seismic intensities. On the basis of predominant roof and wall materials, buildings were classified into 4 basic categories [7]:

Category – A

A1. Mud Wall – All roofs sloping

A2. Unburnt Brick – (1) Sloping roof, (2) Flat roof

A3. Stone Wall – (1) Sloping roof, (2) Flat roof

Category – B

B. burnt Brick Wall – (1) Sloping roof, (2) Flat roof

Category – C

C1. Concrete Wall – (1) Sloping roof, (2) Flat roof

C2. Wood Wall – All roofs

C3. Ekra Wall - All roofs

Category – X

X1. GI and other Metal sheets – All roofs

X2. Bamboo, Thatch, Grass, Leaves – All roofs

This classification was adopted from Census of Housing, Government of India (GOI), 1991.

3.2 Creating Controllers

Controllers were created to define methods operable on the stored data or the computed data. All logical aspect of this application was applied to the controller section.

3.3 View or HTML Sheets Design

This was the interface developed for user interactivity with the data. This was the most crucial part to develop as it involved amalgamation of various technologies for the betterment of application. Google maps were incorporated in order to visualize location based earthquakes. Overall view architecture was classified into following categories:

3.3.1 Search Options

Information related to earthquake records were classified on the basis of 4 prime parameters and their combinations as shown in Figure 1.



Figure 1 Front- End Search Options

These parameters were Magnitude, Year, Location and Radius. There combinations were formed by considering them together with remaining parameters (One by one and all together in some cases). The flexibility incorporated by this classification was the ease with which an end user can search the earthquake records based upon the ranges or limits incorporated to these parameters or their combination by the end user. Moreover the range selected from this view section goes to the controller where instructions were defined to mine out earthquakes those comes in the selected range and then to project these screened records onto the Google maps in the view section. This overall flow of information from Views to Controller to Models and again from Models to Controller to View makes this application more interactive and view more free from data dependency.

3.3.2 Data Processing and Projection

It is not always the case where information to the end user directly comes from the database. In most of the cases we have to process the information first and then only we can project it on the view for the end user. This fixes the interactions among the model, controller and view. For example in case of Seismic Risk evaluation, we have considered 2 prime factors for the risk index computation. These

factors do not come directly from the database. Rather depending upon various other factors, these 2 risk evaluating factors get fixed somewhere in between before getting projected onto the View. Like in case of hazard computation input from the end user will be the location coordinates or the name of the region for which he wants to evaluate the seismic risk. The first task for this application was to evaluate the zone in which this location lies. This all computation took place in controller and finally the result obtained from the controller goes directly into the view. Here no controller – model interaction is involved.

4. APPLICATION FEATURES

For the hazard estimation, determination of seismic zone is required for the queried location. Latitude and Longitude were used as an input to define a queried location. This was made more interactive by using prototype, a java script library supplied free with rails. Problem with Google maps was its limitation of taking location info on the basis of location coordinates (latitude, longitude). But location coordinates are not the most used representation of location by common people. Most of the people identify their location either by name or by an associated event. Here we considered name based location identification as the most common trait and tried to implement a conversion code from location coordinates to location name in the controller method as shown in Figure 2.

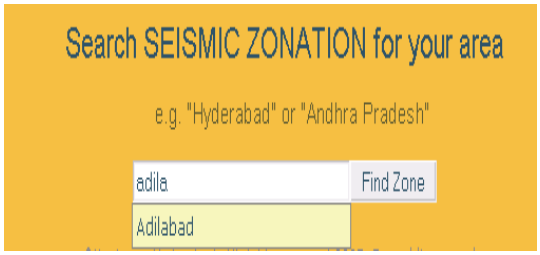


Figure 2 Seismic Zonation Search

This made application flexible in terms of input parameter and friendlier in terms of user's needs. On the other hand for vulnerability assessment, after fixing the location, one additional parameter i.e. type of houses is required. This necessitates estimation of types of construction in the locality of the queried location. So a feature was developed through which regional parameters could be queried using queried location as the centre and any radius (R) for which the region has to be defined. This location – radius based query for finding earthquakes in a radius of 500 Km of Delhi region as shown in Figure 3.

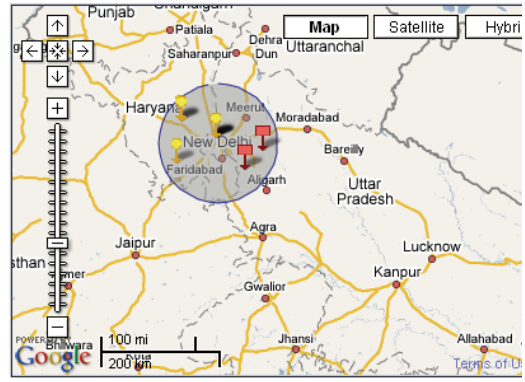


Figure 3 Location – Radius Based Search

4.1 Additional Features

Seismic Risk alone is not enough to mitigate the harms of a seismic disaster. The most important before or during a calamity is to share knowledge and information in the concerned community. This application was raised further into 4 different categories to fulfill this aspect of disaster mitigation. These categories are shown in Figure 4.

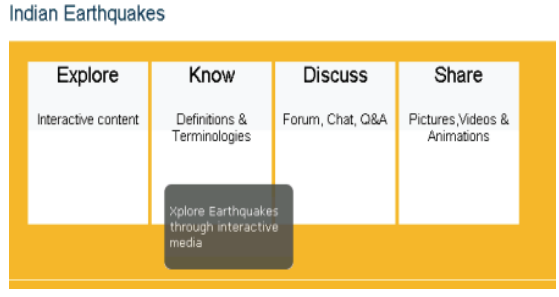


Figure 4 Four Major Categories for View

Explore section was kept for the interactive features of this application. Interactive features like those involved simple projection or computed results from the earthquake records. Know section was developed for the general information related to the terminologies and information related to the

seismology. Discuss section was kept to make application more interactive in terms of end usage. This section was supplied with a forum, chat and a question answer segments in order to provide an online platform for discussing seismological termsand events. Share section was developed with a vision to make people share and download multimedia content related to seismology.

5. RESULTS AND DISCUSSION

So far application has been developed to incorporate hazard computation by identifying the seismic zone of the queried location. Database for vulnerability assessment is yet in a developing phase. Database for Indian earthquakes that struck in past 300 years was developed. Additional features like parameter based earthquake query, their count and related information display were incorporated. All the earthquakes and related information can now be visualized more thoroughly onto the Google maps as shown in Figure 5.

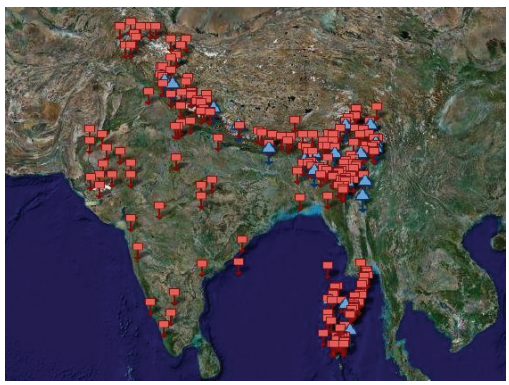


Figure 5 Projection of Earthquake on GoogleMap

6. CONCLUSION

As discussed in this paper, evaluation of seismic risk of an area is prerequisite for any planning and mitigation activities for seismic disasters and if it is available with us in advance than half the task of data collection is over. The application developed here will provide the seismic risk details based upon hazard and vulnerability of any particular region of the country. Thus providing significant information will help in planning and mitigating the seismic disaster along with sensitizing the general public through easily accessible and fast growing medium of web.

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A FRAMEWORK FOR THE REALIZATION OF NETWORKED ROBOTS AND HUMAN BEINGS

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ABSTRACT

With a recent surge in robotics research, the need to develop a platform for robots and human beings to interact and co-exist has become imperative. Though advances in Internet technologies have enabled devices including robots to be plugged onto the network, a lot of hurdles still remain. In this paper we present an architecture of a social system of both robots and human beings wherein the entities co-operate over networks by sharing intelligence and building faith on each other. Faith makes the entities to interact more intensely thereby forming a social system.

KEYWORDS

Networked Robots, Information Sharing, Faith, Social System

1. INTRODUCTION

Robotics is a field that has many existing potential applications. Most often the expectations from the robots do not match current realities. The crux of the problem however, is to achieve this with real robots in real environments and in real time. In the early stages of development of networked robots, many robots were teleoperated [1, 2, 3]. The advances in Internet technology has thrown open a new era of Internet Robots [4, 5]. Internet based robots have been designed to perform some predefined tasks. The user does not have the flexibility in controlling the robot to cater to his needs. Further these robots lack facilities for reprogramming and sharing of intelligence. Data or knowledge acquired locally by the above methods cannot be used by or shared with other robots or devices on the Internet. *i*RobIN [6] provides a framework for sharing intelligence on Robin-II [5]. MANER [7] provides a routing protocol for an Ad-hoc Network of Robots. The work described in this paper is an extension *i*RobIN [6] and MANER [7] and envisages to provide intelligence more efficiently for an open architecture where all possible ways of communication viz. human-human, human-robot and robot–robot co-exist. *i*RobIN is mainly a centralized system and a failure of its central intelligence server, designated the Intelligent Access Point (IAP), even for a small duration could result in the failure of the entire system. By introducing the concept of *faith* amongst robots connected to the network we aim to reduce the burden on the IAP by allowing robots to directly communicate with one another. The concept also makes the entire system more fault tolerant in the sense that even if the IAP is down the robots will still thrive using information shared amongst their peers. It is envisaged that the architecture explained herein may be used in diverse situations including construction scenarios. Computerized numerical controls in construction equipment could be controlled over the network and made to communicate and interact with each other more effectively to improve construction oriented performance. Robots deployed in construction scenarios can also monitor and interact with these machines as also humans to increase overall efficiency and safety.

2. COMMUNICATION ARCHITECTURE

In this paper we describe a new architecture to provide an easy way of communication between Networked robots and human Beings. The architecture as mentioned is an extension of *i*RobIN [6] framework with the concept of *faith* introduced to enhance sharing of knowledge and experience gained by individual robots. Thus doing so, it helps to provide an easy way for the creation of a co-operative human-robot society over a network. The proposed faith network layer leads to a faster method of sharing the learned information amongst the robots. Figure 1 depicts the overall architecture of the system.

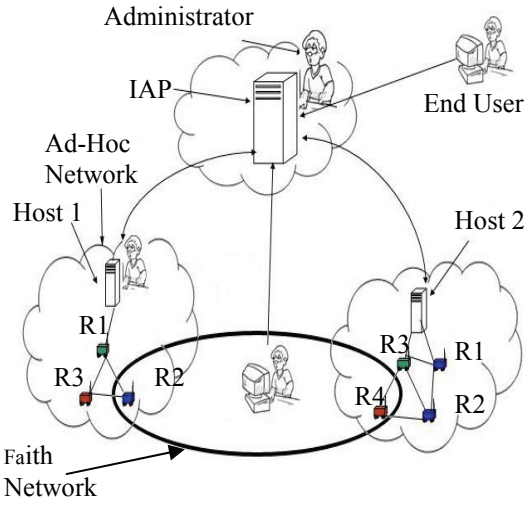


Figure 1 The Communication Architecture

The main components of the system include Robots, Human beings, Hosts (A server which act as a link between the Mobile Ad-hoc network of robots and the rest of the system.) and the IAP. Each robot can be heterogeneous in their functionalities. All of them share information hosted at the local host that controls it. The word information could mean, for instance, the various situations that the robots faced and the corresponding moves taken by the robot to overcome the situation. Knowledge sharing between robot-robot and human-robot enables a better control on the society of robots and provides for better utilization of the robots. When a robot is to be connected to the network, it has to have an ID. The host that caters to robot initially subscribes to the central server viz. the IAP. In doing so, the IAP confers a Global Network Identifier (GNID) that identifies the host. Robots in turn have to subscribe to the host and the latter allocates a Robot Identifier (RID). Thus the robots, which form the final nodes, are identified by a GNID:RID pair within the network. Likewise human beings can also join the network by subscribing to the IAP and be identified by a Human Identifier (HID). Robots under the same host (H1) such as R1, R2, and R3 may constitute an Ad-hoc network as in MANER [7]. Communication amongst robots under a different host, for example R1 in H1 and R2 in H2, initially occurs via the IAP. We have used methodologies similar to *i*RobIN [6] to achieve this. Robots communicate with other entities in the network on-demand. Scenarios where such communication is essential include those when a robot is stranded and is unable to recover from the situation. Under such conditions it sends a request query for help via the host to the IAP. The IAP in its turn retrieves the robot configuration information (make, sensors mounted, etc.) stored at the time of registration to search for other similar robots in the network. It then contacts each of them to find possible solutions obtained from them and sends the best solution back to the requesting robot. The requesting robot selects and effects a solution. If it is able to recover from the problem at hand it builds *faith* in the robot/human being from which it obtained the solution. Faith of one robot on the other depends on the solution provided by the robot, the number of interactions with that particular entity and the frequency of communication.

2.1. IAP (Intelligent Access Point)

The Intelligent Access Point (IAP) is a remnant of the *i*RobIN [6] architecture. It acts as a central server for the entire system. The IAP stores the information about all the robots, devices and human beings. This includes configurations of the robot, information of its environment, query log for keeping track of the queries under processing and a Global Network Identifier (GNID) of each host. Equivalent information on human beings viz., name, Human Identifier (HID), area of interest, etc. are also hosted on the IAP. The IAP facilitates searching for the solutions to queries from the robots in the network. The querying robot attaches its GNID, RID pair in the query packet. The IAP

performs an exhaustive search on the network and finds all robots that have the same configuration. The search facilitates the finding of that robot which is very similar to the querying robot. The best match based on the robot configurations is found using equation 1.

$$M = \sum_{i=1}^{N} F_i \text{ ,where } F_i = \begin{cases} 1, if\ S_{i=}Q_i \\ 0, if\ S_{i\neq}Q_i \end{cases} \quad (1)$$

where F_i is the match flag corresponding to i^{th} sensor on the querying robot, while M indicates the degree of match between two robots, S_i is the i^{th} sensor of the solution-providing-robot (the port, position and type), Q_i is the i^{th} sensor of the querying robot (port, position and type). The environment information is not currently included in the implementation but it may also be taken into account. Using the above search criteria, it was found that the robots forming faith have similar configurations and also imbibe similar behavior. Once the best match is found the IAP forwards the query to the corresponding hosts. The hosts in turn search in their respective local databases of the concerned robot(s) for sensor conditions identical to that posed by the querying robot. The hosts retrieve the corresponding actions taken and return the same to the IAP. The IAP then forwards the solution, GNID:RID pair and the IP address of the solution-providing robot to the host which controls the querying robot. This host stores the GNID, IP address from the solution packet and removes the IP information and forwards it to the querying robot as the solution. The IAP maintains a list of the best matches in order to enable the querying robot to ask for information from the remaining set of robots in case the solution from the first one fails. During the initial stage, the IAP acts as the central server for the whole network since all queries are forwarded to it. This could result in increase in server load. However as the system strengthens in faith building amongst the entities, the load in IAP is bound to reduce.

The IAP contains two servers as shown in the Figure 2 - a web server which is set up for catering to the human clients and another communication server for communicating with the robots.

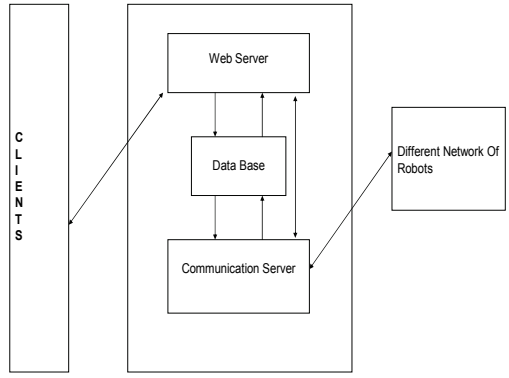


Figure 2 Internals of IAP

2.1.1. Web server

The web server provides a graphical interface to a registered human member so that they can obtain all related information about the whole system of robots and human beings. Other facilities provided by the IAP to the user via an interface include -

1) *Human Centric Information*: This interface shows all the members of system who are online and also helps to send messages to them. A new user can also register to the system by submitting his details to the interface.
2) *Robot information*: This helps the user to view all the robots, which are presently attached to the system. It also provides a simple way to program the robot remotely. The user can send a minimal number of high-level instructions to the robot. These are then interpreted at the robot host.
3) *Inbox*: The registered members also have an inbox facility where the user can receive messages from other entities (human beings and robots).

2.1.2. Communication server

It provides an easy way of robot-robot and human-robot interaction. The various modules within the communication server are as follows.

1) *Host Registration:* When host registers to the system, this function procures the IP address from the packet and issues a Global Network Identifier (GNID) to the host. The IAP stores this GNID, IP pair for future mapping of GNID to IP address.

2) *Procuring Robot configuration from host:* The job of this function is to procure the robot configuration and its Robot Identifier (RID) from the packet. The information is stored in a database for future use (for example searching for a particular robot with some specific property).
3) *Searching for solution:* This function provides a way to search for the best matched robot according to the querying robot. The input to the function is the RID, GNID pair of the querying robot and the output is a set of GNID, RID pair of robots that best match the configuration of the querying robot.

2.1.3. Database

Both servers (Web server and Communication server) use common databases. For example some of the databases used at the IAP include -

The Host table: This contains the GNID and IP address required for mapping of GNID to IP address. The entry in this table is stored when the host registers at the IAP and receives a GNID from the IAP.

The Human table: It contains all relevant information on the human beings. This includes personal information (Like name, age, sex), contact information, information on whether the human being is logged in or not, an alternative device number (for example PDA) and whether or not the human being is a deployer of a robot, etc.

The Query Log table: This contains the information of a particular global query; for instance the RID: GNID pair of the querying robot and the status information of the query. It is used to trace a robot in the network and find whether or not it is replying to a request for a solution.

2.2. Host

The host acts as a link between the robots and the IAP. If a deployer wishes to setup an ad-hoc network then its host has to go through the process of registration to get a global network identifier (GNID). The host stores information about the robots under its jurisdiction (eg. robot identifier issued to them at the time of registration process), solutions to the problems faced by the robot(s), and the faith built up by the robots on others.

2.3. Robots

The robots form the nodes of the network and are under the jurisdiction of a fixed host. It stores its Robot Identifier (RID) issued during the registration process. The robot also holds the GNID of the host to which it remains attached. Thus the RID: GNID pair makes the robot uniquely identifiable in the social system. It uses this pair as an identifier for further communication to other entities in the social system. The robot also stores the information on the possible moves taken to overcome an unexpected situation and the faith information on other robots. As the size of the memory on board a robot is limited, such information is periodically transferred to the respective host.

The robot can generate three types of queries Local Query (LQ), Global Query (GQ) and Faith Query (FQ). All these queries have dynamically varying response times. The Host, which controls the robot, keeps track of the average response time. Based on this the robot autonomously decides which of the queries should be used to procure assistance and in what order.

The various functions that are hosted on robot are given below:

1) *Generate Local Query:* The function takes the sensor values as the input parameters and generates a local Query for the robot. The local Query is forwarded among all the robots in the ad-hoc network to which querying robot belongs.
2) *Generate Global Query:* The function generates a global query for the robot by taking its sensor values. This Query is forwarded to its Host, which in turn forwards it to the IAP.
3) *Generate Faith Query:* This function also takes sensor values as the input parameters and generates a faith query for the robot. The function finds the best robot (one on which it has highest faith) from the faith table and forwards the query to its host with the robot's GNID: RID pair. The host in turn forwards it to the corresponding host under which the highest-faith robot is attached.
4) *Decide the Order of Query:* Robots maintain the average faith query, global query and

faith query response times as three state variables. With each query, a robot also generates an expected time indicating the amount of time it can wait to procure a solution. This function takes the parameter - *Expected time* - as input and finds the possible queries that a robot can ask. If more than one query is possible, the function can decide the order in which the query should be asked so as to minimize the response time.

3. COMMUNICATION SCENARIOS

Communications amongst the entities of the system could occur in various ways some of which have been highlighted below.

3.1. Robot to Robot

To illustrate the need for communication we use a simple problem of robots, R3 and R4 under Host 1, (as in figure 1) trying to find green spots on the floor. Another robot, R2, under a different host (Host 2) requires to be stationed on green spots to gather energy. If the robot R2 under Host 2 is unable to find the same after repeated trials in its environment it generates a query in one of the following ways:

Case 1 Global Broadcast Query

If the robot is not able to get a solution from local query (LQ), R2 generates a Global query and sends it over to the IAP. On receiving it, the IAP which hosts information on all robots, identifies all those robots which closely match/resemble the configuration and environment information of the querying robot and sends the query to each of them. The robots in their turn respond if they have a solution to the problem. The IAP consolidates, ranks all solutions and sends the best solution to the robot via its host. The querying robot tries to execute the solution and in doing so may or may not recover from the problem at hand. If it does, it informs its host which builds on the faith of this robot on the one that supplied the solution. The robot tries other solutions, if it does not succeed. If R3 and R4 under Host 1 have already discovered ways to find the green spots, it is highly possible that R2 of Host 2 will get a solution from either of them. In this way R2 manages to accomplish its task (even though it has not been programmed for that particular event) by requesting for aid from other robots. If all solutions prove futile it tries a random move or assumes it is stuck and contacts its human master.

Case 2 Faith Query

The building of faith amongst the entities transforms the network into a social one. Whenever a robot obtains a correct solution from either of its siblings (LQ) or from its cousin entities (GQ) it builds a faith on the entity that provided the solution. This faith is maintained in the form of counters for each robot in their respective hosts. These counters are increased or decreased based on whether the solution yielded a good or a bad result. The following equations were used to test the generation of faith among the entities in the network. The value of faith is governed by Equation 2 [8].

$$F_{ijNew} = F_{ijOld} + (R_i^j - P_i^j) \Big/ \sum_{k=1}^{N} I_{ik} \qquad (2)$$

where F_{ij} is the faith built so far of robot *i* on robot *j*. R_i^j and P_i^j indicate rewards and penalties obtained by robot *i* after an interaction with robot *j*. I_{ik} indicates the total number of interactions that robot *i* had with robot *k*. A robot *i* is said to have robot *j* in its virtual faith network if and only if

$$F_{ij} > \mu \qquad (3)$$

where μ is the upper threshold of faith. The faith value is reduced after a timeout period proportional to a Time-To-Live (TTL) governed by the equation 4.

$$TTL_{New} = TTL_{old} + c_1 R_i^j - c_2 P_i^j \qquad (4)$$

where c_1 and c_2 are constants. The generation of faith prevents the robot from making a global query. Instead it directly contacts the robot on whom it has built the faith thereby (hopefully) gaining a solution in lesser time. Such queries have been termed as Faith Queries (FQ). These queries naturally consume far less time than their global counterparts.

3.2. Human to Robot

A human user may also participate in being an entity by the interface provided by the web server

hosted at the IAP. He/she can send commands either to control a robot or get information on its status. A set of commands constituting a small program may also be sent.

3.2. Robot to Human

When a robot wishes to interact with a human being or its deployer to get some assistance, it can request the IAP to send a message to the specified person. The IAP forwards this message to the deployer's *inbox*, who in turn can check it as and when he is online. Such a scenario can occur when a robot does not get a feasible solution from any robotic entity on the network.

4. APPLICATION TO CONSTRUCTION SCENARIOS

Large construction sites require constant interactions between the people involved as also the monitoring of the machinery used. Robots forming the network described herein could be appropriately programmed to monitor precarious construction scenarios. Material handling as well as requirements at various sections of the site could be monitored and managed using such networked robots. The need for a particular material (for instance bricks, tiles, cement, etc.) could be identified by the robot on the job and relayed to other entities (robots and/or humans) in the network. Scenarios where a demolition is to take place could require robots to operate in co-operation to find the strength of a particular region which could otherwise be dangerous for human beings. Sensory probes mounted on robots could find the relevant parameters and relay them through other robots in the ad hoc network to reach the human user. Since the networked robots described herein can be programmed to co-operate and learn, it is possible for a human user to tailor them to suit the needs of the construction scenario. A large task force of robots comprising the nodes of the network can prove to be a vital aid to humans working in a construction scenario. Since the humans also comprise of nodes in the network, the degree of interaction with the robots within the person's vicinity increases, effectively enhancing throughput.

4. CONCLUSIONS

In this paper we have introduced a framework that can facilitate an easy communication between networked robots and human beings. Such systems can sustain only if proper communication channels are thrown open between every entity that constitutes the network. It was found that the IAP acts as a central server only initially. As inter-entity faiths are strengthened with the passage of time, the IAP seemed to play a lesser role in communication. With a decrease in the server load new entities can get their requests processed at a faster rate. As part of the future work, we are intend to incorporate more features to facilitate efficient remote programming methodologies as also adding devices as entities of the network.

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GUIDING ROBOTS USING MOBILE PHONE

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Abstract

Communication via mobile phones is becoming increasingly common among humans but next in the pipeline is communication between human and robots. This project promotes wireless connectivity which makes it hassle free affair. In this paper we propose the concept of controlling a robot by a mobile phone from a remote area. The robot supports two ways of communication as it can receive commands by a mobile phone and in other way round it can send data through cell phone to the user. This prompted us to use a PC and its serial port with RS232 protocol. The user sitting at a distant place can send sms's to control the robot placed far away from him (even in another continent). The sms is decoded in a PC by a program which then sends command to the robot via serial port. Similarly the robot can send information about the working environment condition received from its sensors. This data is converted to proper PDU or TEXT mode as needed by the mobile phone which is forwarded to the operator by a sms. This involves a NOKIA 6020 phone and an 8051 microcontroller (AT89C52). A RF module, connected to a computer's serial port, can operate at two frequencies, one for communicating with the robot and another for the mobile. The cell phone's TX and RX pins are connected to the serial port by the RF module and a MAX232 IC. The RS232 protocol does not support TTL logic so a line driver such as MAX232 has to be used to convert TTL logic levels to RS232 voltage level .The phone converses with the computer by AT commands sent through the serial port. A practical implementation of this project may witness applications such as home automation and security.

KEYWORDS

Mobile, AT Commands, Serial Port

1. INTRODUCTION

In this paper we present control of a robot by a cell phone via a computer. It suits many needs as it provides an implicit wireless communication between the user and the robot notwithstanding the distance between the robot and the user. It has certain advantages over other wireless modes as the user can control the robot and monitor applications like home automation and security without being physically present near the robot.

The user sends instructions from his mobile to another mobile connected to a PC.The memory of the latter is continuously scanned by a programme running in the PC .The instructions received in form of sms is compared with any predefined instructions in the programme.If a match occurs then computer sends appropriate commands to the robot via serial port. Simultaneously the user receives the desired information from the sensors.

2. COMPONENTS OF THE AUTOMATED SYSTEM

The entire automated system can be divided basically into two parts:

1. Hardware
2. Software

The hardware of this project is divided into two parts:

1. Cell phone interfacing with the PC: The cell phone is directly connected to the serial port of the PC via RF module. It can also be connected to the

usb of the PC as it facilitates faster data transmission and supports the connectivity of as many as 128 devices simultaneously.

2. Robot interfacing with the PC: The robot is interfaced with the PC's serial port via RF module. An 8051 microcontroller (MC) forms the heart of the robot controlling and servicing the various sensors of the robot. A MAX 232 chip is used to facilitate communication between the MC and the PC to commensurate TTL logic of the MC with the RS 232 standard of the PC's serial port. The sensors form a link between the MC and the surroundings whose input data is forwarded to the user.

The software demands of this project are:

1. A programme running on the PC to continuously scan the phone/SIM memory of the cell connected to the PC and to send (instructions) and receive data (sensors) from the robot.

2.A programme for the MC to control the robot, send instructions to the actuators, receive data from the sensors and send data to the PC that the user requests .

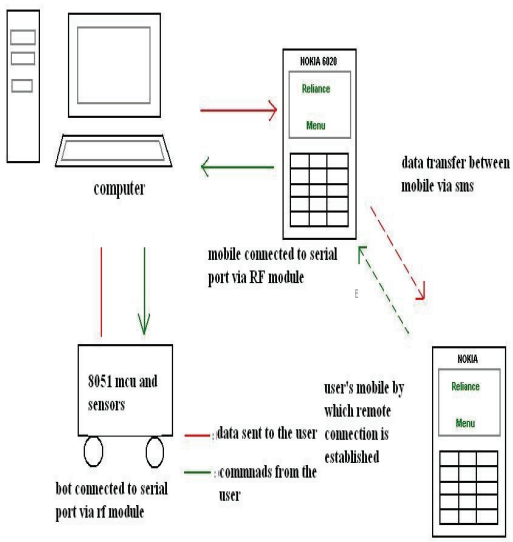


Figure 1

3. HARDWARE

The heart of the circuit is an 8051 MC (AT89C52) and a dc motor driver BA6209.The block diagram is given below. Sensors like heat, obstacle sensors are connected to it which can send information about environment to the pc which is forwarded to the user via sms.But since hardware of robot is very common thing this paper concentrates on the controlling method of robot by mobile phone rather than the hardware of robot.

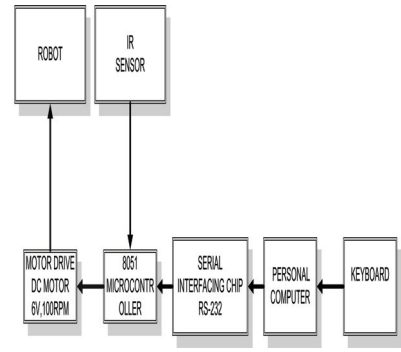


Figure 2

4. MOBILE COMMUNICATION

For communication of mobile to a PC one first needs to know the mobile's IO capabilities. If it has IrDA or Bluetooth then things are much easier because no cables are needed, but if the mobile (or the PC) has no such features then an appropriate data cable may be used provided the cell has port for USB data cable. However the most common IO capability is the serial line, though it is not in the form of the well known RS-232-C standard of PC's serial port but in the form of what is called as FBUS and MBUS.The MBUS is a half-duplex method used in older Nokia phones. With MBUS it is possible to interface with almost all Nokia mobile phones for service and adjustment purposes. The FBUS is a newer solution and offers high-speed full-duplex communication link between the phone and the computer. The service and adjustment operations which are traditionally made over MBUS are available in FBUS too, but usually much faster.

4.1 Mbus Method of Communication

The communication methods called FBUS and MBUS are used in Nokia mobile phones for data transmission, service, and adjustment. The MBUS method that uses only a single pin is a half-duplex method used in older Nokia phones. With MBUS

it is possible to interface with almost all Nokia mobile phones for service and adjustment purposes. The FBUS is a newer solution and offers high-speed full-duplex communication link between the phone and the computer. The service and adjustment operations which are traditionally made over MBUS are available also in FBUS, but usually much faster.

4.1.1 Details of Mobile Phone Hardware

The figure below describes the pin outs of data cables of NOKIA phones.

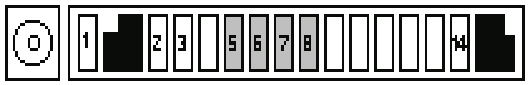


Figure 3

The 14 pin pop-port contains signals for hands free microphone, stereo speakers, FBus Rx/Tx or USB signals for the phones supporting them, power output for feeding the accessories that don't have their own batteries, and the Accessory Control Interface (ACI), a bidirectional serial control bus for connection of phone accessories, with a proprietary protocol.

Table 1

Pin Number	Pin Name
5	USB Vbus
6	FBus Rx/USB D+
7	FBus Tx/USB D-
8	GND

4.2 The Circuit Diagram

The whole project is implemented using NOKIA 6020 mobile so fig 4 shows the detailed circuit connection.

5. AT COMMANDS

After connecting a mobile phone to a computer, it can be controlled by sending instructions to it. The instructions used for controlling the mobile phone are called AT commands. Commands are to control the sending and receiving of SMS messages.

The following table lists the AT commands that are related to the writing and sending of SMS messages:

Table 2

AT command	Meaning
+CMGS	Send message
+CMSS	Send message from storage
+CMGW	Write message to memory
+CMGD	Delete message
+CNMI	SMS Alert
+CMMS	More messages to send

The AT commands are written in vb6.First any message received on the mobile is read. Then they it is decoded into a user friendly format. From that command is read and it is issued to the microcontroller through serial port for further action.

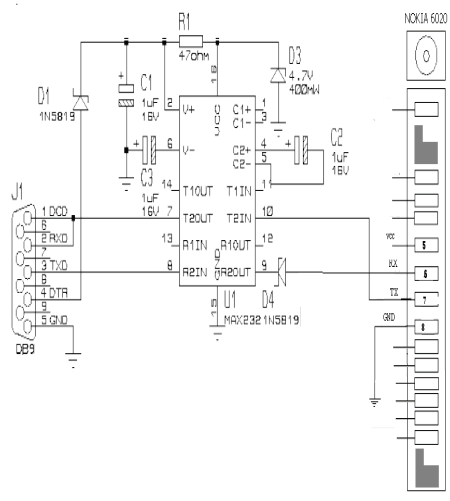


Figure 4 The Circuit Diagram

5.1 Use of SMS

Since short text messaging popularly known as sms is the most widely used and the cheapest service available in mobile service, it is used to control our robot. The SMS message, as specified by the Etsi organization can be up to 160 characters long, where each character is 7 bits according to the 7-bit default alphabet. Eight-bit messages (max 140 characters) are usually not

viewable by the phones as text messages; instead they are used for data. There are two ways of sending and receiving SMS messages: by text mode and by PDU (protocol description unit) mode.

5.2 The PDU Format

The text mode (unavailable on some phones) is just an encoding of the bit stream represented by the PDU mode. Alphabets may differ and there are several encoding alternatives when displaying an SMS message. The most common options are "PCCP437", "PCDN", "8859-1", "IRA" and "GSM". These are all set by the AT command AT+CSCS, when some one reads the message in a computer application. If you read the message on your phone, the phone will choose a proper encoding. An application capable of reading incoming SMS messages can thus use text mode or PDU mode. If text mode is used, the application is bound to (or limited by) the set of preset encoding options. In some cases, that's just not good enough. If PDU mode is used, any encoding can be implemented.

5.2.1 Message in the PDU mode

The PDU string contains not only the message, but also a lot of meta-information about the sender, his SMS service center, the time stamp etc. It is all in the form of hexa-decimal *octets* or decimal *semi-octets*. A PDU looks like a long hexadecimal string, representing the number of the network operator's SMS central (Service Centre Address, SCA) chained to the whole packet used in the SMS transport layer (often referred as Transport Protocol Data Unit, TPDU). The latter includes many sub-fields in addition to the message text itself. Most data is packed to save bits.

The first packet is the SMS-SUBMIT, used for sending a message; the second is the SMS-DELIVER packet, for receiving. The subfields are detailed in the following table:

Table 3

SCA	Service Centre Address	Network operator's Service Centre number. Not required by some mobiles. An hex value of 00 or 01-80 means "unknown": the mobile will use the default number stored in mobile's settings.	1 or 2 to 12 bytes
ID	TPDU type identifier	SMS-DELIVER or SMS-SUBMIT identifiers and flags (e.g. request of a status report or presence of VP field) .	1 byte
MR	Message Reference	Progressive number (0 to 255).	1 byte
OA or DA	Originating or Destination Address	Sender's or destination phone number. Note that a different number encoding from that of SCA is used.	2 to 12 bytes
PID	Protocol Identifier	Nature of data transported (FAX, voice, etc.), used by the Service Centre for a better routing.	1 byte
DCS	Data Coding Scheme	Format of the data transported (7 or 8 bits, alphabet, etc.) and where to store it (Mobile memory, SIM module, or for immediate display).	1 byte
SCTS	Service Centre Time Stamp	Year month, day, hour, minute, seconds and time difference with respect to GMT.	7 bytes
VP	Validity Period	How long the network operator service centre will hold the message, if undelivered (A7=24 hours).	0, 1, or 7 bytes
UDL	User Data Length	Length of data, prior to encoding (e.g. 11 7-bit characters fit into 10 bytes).	1 byte
UD	User Data	message data	0-140 bytes

5.2.2 Phone numbers packing

Phone numbers start with the number's length, intended as field length in *bytes* for the service centre (SCA), and *digits* for the remaining numbers (DA, OA). The second byte specifies the numbering plan: 80 = unknown, 81 = national number, 91 = international number.

Then follow the digits, swapped in pairs and each occupying a nibble. If the length is odd, the unused nibble (*semi-octet* in ETSI language) is padded with $F. Some mobiles don't require the SCA, or accept 00 or 01-80 as valid values for the service centre address: in that case the mobile will use the default service centre number.

5.2.3 Message packing

A SMS message, according to ETSI specification, can be up to 140 bytes long (*octets* in ETSI terminology). The usual GSM alphabet requires only 7 bits per character (a *septet*), allowing for the packing of up to 140 * 8 / 7 = 160 characters. So the received sms is packed as explained above. So the mains algorithm keeps scanning the whole PDU string containing hexadecimal numbers. Then it separates out the sender's no and then compares with previously stored values. If the sms is sent by authenticated person then it searches for the message part. After saving the message into a variable it compares with the previously stored message. If the received message is exactly what is stored then it issues commands accordingly to the robot through serial port.

6. RADIO FREQUENCY COMMUNICATION

Due to the need of controlling robots and cell phone simultaneously through one serial port RF communication is used. Details of RF communication are explained below.

6.1 RF Transmitter Interface

For communicating the robot with pc TX-4-PC is used. It connects the Holtek HT-12E remote control encoder IC, Ming TX-99 RF transmitters. It is connected directly to PC's serial port. The advantage of using these transmitter modules is the loop antenna designed into the RF module. The loop antenna allows operation between 30-50' [or more] without the addition of the external wire antenna. Now since it's connected to the PC's serial port it's fully controlled by the serial commands written in our program.

Serial Commands to Control the TX-4-PC:

The Transmitter waits for a serial command string consisting of three data bytes from the PC serial port as shown below.

• Byte #1 = Synchronization byte [170]

• Byte #2 = 8-bit address of receiver to control [0 to 255]

• Byte #3 = 4-bit data [0 to 15]

The synchronization byte 170 consists of an even number of 1s' & 0s', or 10101010 in binary, and is used to synchronize the transmitter with the PC serial port. The address byte selects the receiver at a specific "address" to control. Data packets not preceded by the synchronization byte of "170", will be ignored. This helps the TX-4-PC ignore any noise signal that may otherwise be interpreted as a beginning data packet. The 250mS pauses in the VB application software is given to take into account the 200mS time frame in which the transmission occurs. An additional time of 50mS per pause ensures the transmitter has returned to the data input routine, and is ready for the next inbound data/control packet. This causes four transmissions from the TX-4-PC to help ensure data packets reach the receiver in case of interference.

6.2 RF RECIEVER

For receiver purpose the RX-5 receiver board is designed for use with the TX-4-PC RF transmitter board. The RX-5 receiver board is used with RF receivers. Ming RE-99 RF transmitter module. The advantage is that for instant remote control we just need to plug-in the RF receiver modules .For decoder purpose HT-12D is connected.

Address Feature:

The RX-5 receiver has an 8-position DIP switch used for setting the receiver/decoder address. Addresses from 0 to 255 are possible, allowing control of up to 256 individually addressed receivers, or combinations with multiple receivers set to the same address.

A7 A6 A5 A4 A3 A2 A1 A0

All of the HT-12D decoder IC address pins are at ground with each DIP switch in the ON position for an address of "0". Switches in the down position represent logic "1". In the up or ON position at logic "0".So by the help of these switches the address of the particular receiver is set. Now if this receiver is connected to the robot required for the job then accordingly this address is sent through the transmitter by control software in vb6.

7. CONCLUSION AND FUTURE WORKS

In this paper control of a robot by a mobile phone kept at a remote distance is described. This eliminates the necessity of physical presence of a operator at the working area .With the help of this one can easily control robot or any automated device from anywhere in the world.

- The control software is written in vb6 so that it'll work as a standalone application.
- This algorithm is implemented with microcontroller with low computational power (e.g.8051/31) since they don't contain any tedious calculation.
- In order to get more information about working environment sensors are connected to the robot.

Future work:

- It can be also carried out for the home automation system as hardware requirement is same, the difference being some relays connected to the switches of home appliances.
- A cellular platform can be developed where user can himself set the commands to be sent through serial port.
- This technology can be empowered with computer vision where with the help of image processing pictures and videos of remote areas can be sent to the user via mms.

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OPTIMIZATION
AND
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THE COMBINED EFFECT COMPREHENSIVE LEARNING PARTICLE SWARM OPTIMIZER

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ABSTRACT

This paper introduces a novel and efficient optimization method, the Combined Effect Comprehensive Learning Particle Swarm Optimizer (CECLPSO) to handle the problems of premature and slow convergence with inferior solution prevailing in PSO and its variants. These weaknesses are resolved by introducing the combined effect of two consecutive global best particles contribution on the learning strategies of particles with the integration of Comprehensive Learning. This is in contrast to the original Comprehensive Learning PSO (CLPSO) technique, in which, the particles learning strategy is based on the knowledge of only one global best gbest. The performance of the CECLPSO is compared with basic PSO (BPSO) and CLPSO algorithms, on search efficiency, with the set of benchmark functions of dimension 50. The simulation result clearly indicates that the proposed CECLPSO algorithm prevents premature convergence and obtains better solution over basic PSO and CLCPSO in optimizing higher dimensional multimodal functions.

KEYWORDS

Particle swarm optimization, Learning strategy, CLPSO

1. INTRODUCTION

Evolutionary algorithms are stochastic optimization techniques, which learns and adapts from social behavior of species. To replicate and to use the techniques followed by the species, various researchers have developed natural computing algorithms for optimization problems. The first natural algorithm was Genetic algorithm (GA)[1]. GA efficiently handles for optimizing multi-modal and multi objective function. In spite of its efficiency in producing better solution, it suffers with heavy computational burden to solve complex real world problems. The Particle Swarm Optimization(PSO) is similar to GA, was introduced in 1995 by Kennedy and Eberhart [2-3]. PSO is a population based stochastic optimization technique. This algorithm has been an increasingly popular tool for optimizing realworld problems [4-8]. PSO simulate [4] the social behavior of swarm such as bird flocking, fish schooling to solve optimization problems. To understand PSO, social life of the species need to be analyzed closely. Imagine a group of birds searching food in a bounded area. Let their goal is to find maximum density food in the search space, where food is being scattered with varied density. The maximum density food location corresponds to the global solution in PSO world. No bird knows where the high density of food is, but they know how far the goal is from their present

position. Without prior knowledge, all the birds start searching food randomly. Each can memorize two facts i.e it can remember its own history where it found maximum density of food and also it knows which bird has found the maximum density of food among the whole swarm. The flying trajectory of the birds will be altered with these historical facts which helps in converging towards the global solution. This scenario can be used to solve the optimization problems. In PSO, each single solution is a bird called particle in the search space. All the particles have fitness values, which are evaluated by the fitness function to be optimized. Every particle is associated with two memories i.e. self previous best experience (personal best or pbest) and best experience of the swarm (global best or gbest), these factors decides the trajectory of particle. In the past few years different research have been conducted to improve the performance of the original PSO algorithm [8-14] and are reported to give better solution.

Although different variants of original PSO give better solutions, PSO still suffers with premature convergence and inferior solutions for complex multimodal objective functions.This paper introduces a novel and efficient optimization technique, Combined Effect Comprehensive Particle Swarm Optimization (CECLPSO)to handle the problems of slow and premature convergence with improved solution. The weaknesses are reduced by introducing the combined effect of second consecutive global best particles on learning strategies with the integration of Comprehensive Learning algorithm. This is in contrast to Comprehensive Learning PSO (CLPSO) technique, in which, the particles learning strategies is based on only one global best.The performance of the CECLPSO is compared with the original PSO i.e. Basic PSO (BPSO) [1][2] and Comprehensive Learning PSO (CLPSO) [5][8], on different benchmark functions of higher dimensions. Experimental result shows that CECLPSO algorithm overcomes the premature convergence with better solutions.

The paper is organized as follows: Section 2 briefly describes the BPSO and CLPSO. Section 3 describesproposed CECLPSO algorithm. Section 4 presents the benchmark functions and experimental setup adopted for performance comparison. Section 5 describes the simulation results, and Section 6 concludes the paper.

2. PSO ALGORITHM VARIANTS

2.1. Basic PSO algorithm overview

PSO is essentially an evolutionary algorithm for solving optimization problems, which mimics the artificial life of the swarm of birds or school of fish [4]. Each particles position in a swarm represents the potential solution and is evaluated based on the fitness function. The value of fitness function infers the quality of solution. As the particle fly randomly in D-dimensional search space, the position and velocity of i^{th} particle is represented as $X_i = (x_{i,1}, x_{i,2}, x_{i,3}, \cdots, x_{i,D})$ and $V_i = (v_{i,1}, v_{i,2}, v_{i,3}, \cdots, v_{i,D})$ respectively. With increased iteration, the swarm will move towards the global best position by keeping track of their personal best. In a D dimensional search space The $pbest$ of the i^{th} particle is represented as $pbest = (p_{i,1}, p_{i,2}, p_{i,3}, \cdots, p_{i,D})$ and the $gbest$ of the whole swarm is represented as $gbest = (g_1, g_2, g_3, \cdots, g_D)$. The PSO algorithm updates the velocity and position by the following equations .

$$V_{i,d}^{t+1} = V_{i,d}^{t} + c_1 * rand_1 * (pbest_{i,d}^{t} - X_{i,d}^{t}) + c_2 * rand_2 * (gbest_{d}^{t} - X_{i,d}^{t}) \quad (1)$$

$$X_{i,d}^{t+1} = X_{i,d}^{t} + V_{i,d}^{t+1} \quad (2)$$

Where c_1=2 and c_2=2 are the learning factors which determines the relative influence of cognitive and social component to update the position and velocity respectively. $rand_1$ and $rand_2$ are two random numbers in the range of [0,1]. $V_{i,d}^{t}$ and $X_{i,d}^{t}$ are the velocity and position of i^{th} particle in d^{th} dimension till t^{th} iteration respectively. The $gbest_{d}^{t}$ is the global best in d^{th} dimension till t^{th} iteration and $pbest_{i,d}^{t}$ is the personal best of i^{th}

particle in d^{th} dimension till t^{th} iteration.

2.2. CLPSO Algorithm overview

The CLPSO [5][8] was developed to overcome the problem of premature convergence of BPSO for complex multimodal functions. The learning strategy CLPSO is different from BPSO. Instead of learning from the two best factors i.e. $gbest$ and $pbest$ of the particle simultaneously, in CLPSO, the particles learn either from the $gbest$ of the swarm or particle's $pbest$, or the $pbest$ of other particle of different dimensions. In this, if D is the total number of dimension of optimizing problem then, $k-$dimensions will be randomly chosen to learn from the $gbest$, some of the $(D-k)$ dimensions from some randomly chosen particle's $pbest$ and the remaining dimensions learn from its own $pbest$[5][8].The CLPSO algorithm updates the velocity and position as in [5][8].

3. CECLPSO ALGORITHM

CECLPSO is proposed to overcome the premature convergence with improved solutions especially for multi-modal functions. CECLPSO discussed in three parts (a) Combined Effect of first and second consecutive global best on learning strategy, (b) capturing of the weak particles and then direct these in the direction of better particle, (c) integration (a) and (b) with Comprehensive Learning strategy.

3.1. Combined Effect

The combined effect concept is based on the fact of human life. The human beings often be suspicion about the decision made by single person and hence always take the guidance of the second person for the final decision. Thus the influence of more than one person's opinion. The same situation can be simulated in PSO for optimization. The searching decision will be efficient if second best particle's experience is also considered along with the first. The velocity and position update equations now becomes as

$$V_{i,d}^{t+1} = w^t * V_{i,d}^t + rand_1 * (gbest1_d^t - X_{i,d}^t) + rand_2 * (gbest2_d^t - X_{i,d}^t) \quad (3)$$

$$X_{i,d}^{t+1} = X_{i,d}^t + V_{i,d}^{t+1} \quad (4)$$

3.2. Identification of weak particles

For multi-modal objective functions some of the particles will be trapped in the deep local minima and may not be available for searching the good solutions. These trapped particles are called weak particles and are major source of poor solutions and premature convergence. CECLPSO identifies such particles which gives poor solutions, and then accelerates those particles in the direction of better particle of the swarm. Algorithm 1 shows the piece of pseudo code to identify and accelerate the trapped particles.

Algorithm 1 Identification of weak particles

```
Select ← S_p Selection factor for trapped particles
m ← S_p*NP Number of particles to selected (S_p = 0.5 assumed here for simulation)
q ← NP − m
sortedfitness ← sort(f^{t+1}) 'sort' Arranges the f^{t+1} of the particles in ascending order and stores in sortedfitness
for k ← 1, m do
    for l ← 1, NP do
        Δ=sortedfitness(q + k) − f^{t+1}(l)
        if Δ == 0 then
            X(l) =rand * gbest
        end if
    end for l
end for k
i ← i + 1
```

3.3. Integration with Comprehensive Learning

In comprehensive learning the particles learn from different exemplary at different dimension and time. The comprehensive learning concept is integrated with stated proposal with the refreshing rate of 10. The particle's velocity and position are updated by selecting either of the following velocity and position update equation.

$$V_{i,d}^{t+1} = w^t * V_{i,d}^t + rand_1 * (gbest1_d^t - X_{i,d}^t)$$

$$+ \quad rand_2 * (gbest2_d^t - X_{i,d}^t) \quad (5)$$

$$V_{i,d}^{t+1} = w^t * V_{i,d}^t + rand_1 * (pbest_{f,d}^t - X_{i,d}^t) + rand_2 * (gbest2_d^t - X_{i,d}^t) \quad (6)$$

$$V_{i,d}^{t+1} = w^t * V_{i,d}^t + rand_1 * (pbest_{i,d}^t - X_{i,d}^t) + rand_2 * (gbest2_d^t - X_{i,d}^t) \quad (7)$$

$$X_{i,d}^{t+1} = X_{i,d}^t + V_{i,d}^{t+1} \quad (8)$$

Algorithm 2 presents the detailed CECLPSO algorithm.

4. SIMULATION

4.1. Experimental setup

The simulations were conducted on Windows XP with MatLab and PIV 2.6GHz with 512MB of RAM. The population size of 25, for 1000 iteration. The algorithms were tested on set of ten benchmark functions with dimension 50. The results obtained are the average of 30 trials. The performance comparisons of CECLPSO are done with BPSO and CLPSO algorithms.

4.2. Benchmark functions

PSO algorithms presents the difficulty on multimodal functions with multiple minima, therefore we focus on well-known standard benchmark functions shown in Table 2. The benchmark function are numbered as f_1 to f_{10}. Among ten-mentioned benchmark functions; Dixon and Price f_2, Sphere f_8, Sum Square f_9 and Zakharov f_{10}functions are simple, strongly convex and can be considered as unimodal or multimodal. The Ackley function f_1 at a low resolution the landscape of this is unimodal; however, the second exponential term covers the landscape with many small peaks and valleys. Griewank function f_3 is also multimodal with multiple minima. It has a product term, introducing interdependency between the variables. The Levy function f_4 is highly multimodal with several local minima. The Powel function f_5 is also highly multimodal and has several minima but they are non-symmetrical and are randomly distributed. The characteristic of Rastrigin function f_6 is the existence of many suboptimal peaks whose values increase as the distance from the global optimum point increases. The Rosenbrock function f_7 is characterized by an extremely deep valley along the parabola that leads to the global minimum. Due to the non-linearity of the valley, many algorithms converge slowly because they change the direction of the search repeatedly. The function has a long gully with very steep walls and almost flat bottom.

5. RESULTS

The simulations are conducted on the set of ten standard benchmark functions with dimension 50. The simulation results are categorized in two a) Convergence by the algorithms over iteration,shown in Fig.$1-10$ and b) the average of 30 trials shown in Table 1. The Table 1 gives the complete information about the best and worst value ever achieved by the algorithms over 30 trial, where each algorithm is run for 1000 iteration in a trial.The mean, median and the standard deviation of each algorithm are also presented. The best mean result and best standard deviations achieved by the algorithms are shown in bold. The Fig.$1-10$ shows the convergence graphs in terms of best fitness value achieved by each of the algorithms over 1000 iterations. From Table 1 it can be observed that the mean results of CECLPSO over 30 trials surpasses BPSO and CLPSO on the $f_1(x)$ to $f_{10}(x)$ except $f_4(x)$. CECLPSO especially dominates the$f_1(x), f_3(x), f_5(x), f_8(x)$ and $f_9(x)$ where the standard deviation is almost nil. The nil standard deviation show the robustness of the CECLPSO algorithm. The CLPSO outstands on $f_4(x)$ i.e. on Levy function and obtains comparable solution on $f_6(x)$ too. From the convergence graphs in Fig.$1-10$ it can be concluded that CECLPSO obtains good quality solution and avoids premature converges on $f_1(x)$ to $f_3(x)$ and $f_5(x)$ to $f_{10}(x)$. Fig 4 shows the outstanding performance by the CLPSO on $f_4(x)$.

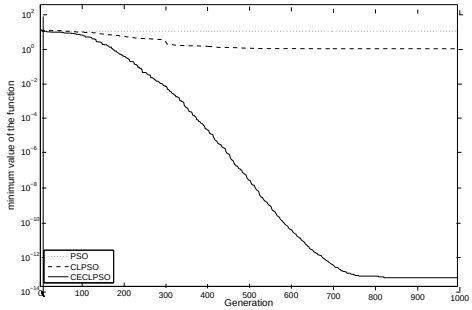


Figure 1. Convergence graph of function $f_1(x)$

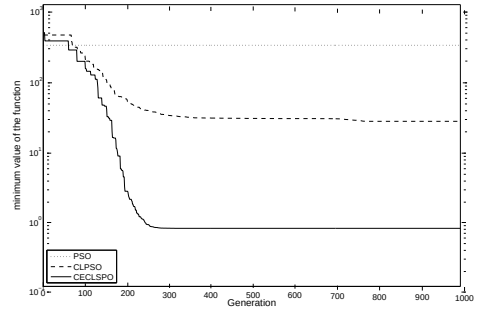


Figure 2. Convergence graph of function $f_2(x)$

Algorithm 2 AEPSO algorithm

Initialize

$Set \leftarrow X_{max}, X_{min}, D, NP$
$V_{max} \leftarrow 0.20 * (X_{max} - X_{min})$
$t \leftarrow 0, i \leftarrow 0$ ▷ *t* for iterations, *i* for particles
Randomly initialize position $X_i^0 \in D$ in R;
Randomly initialize velocity $v_i^0 \leq V_{max}$
Evaluate f_i^0
$pbest_i^0 \leftarrow f_i^0$,
$gbest^0 \leftarrow f_{best}^0$

Optimize

while $i \leq NP$ **do**
Update velocity using either of (5),(6) and (7) equations
Update position using equation (8).
Evaluate f_i^{t+1}
  if $f_i^{t+1} < pbest_i^t$ **then**
    $pbest_i^{t+1} \leftarrow f_i^{t+1}$
  end if
Find $gbest_d^{t+1}$
  if $gbest_d^{t+1} < gbest_d^t$ **then**
    $gbest_d^{t+1} \leftarrow gbest_d^t$
  end if
  $i \leftarrow i + 1$
end while
If stop criteria not met increment t.
Go to step 9.

Report results

Terminate

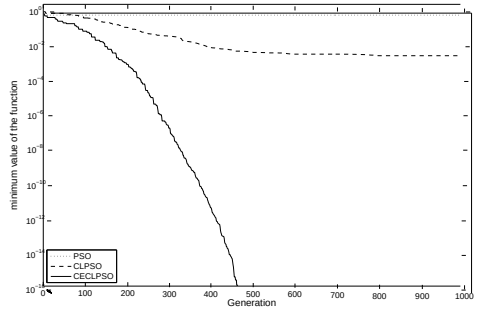


Figure 3. Convergence graph of function $f_3(x)$

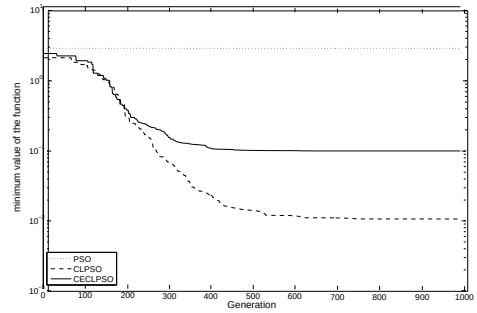


Figure 4. Convergence graph of function $f_4(x)$

6. CONCLUSION

In this paper, BPSO and CLPSO algorithms are compared against CECLPSO. Ten standard

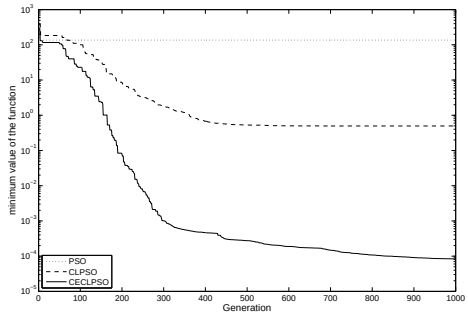


Figure 5. Convergence graph of function $f_5(x)$

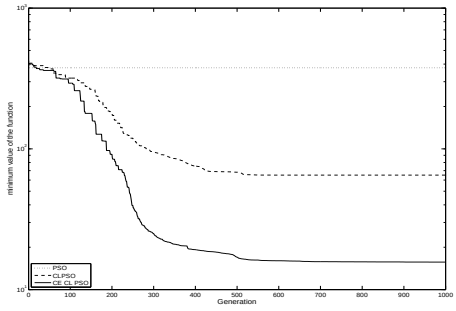


Figure 6. Convergence graph of function $f_6(x)$

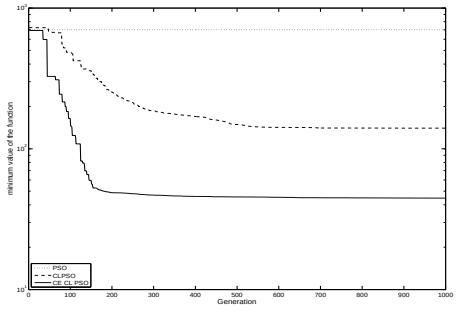


Figure 7. Convergence graph of function $f_7(x)$

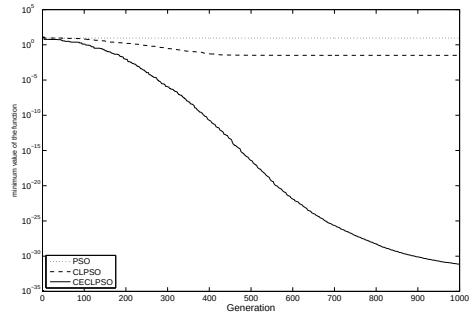


Figure 8. Convergence graph of function $f_8(x)$

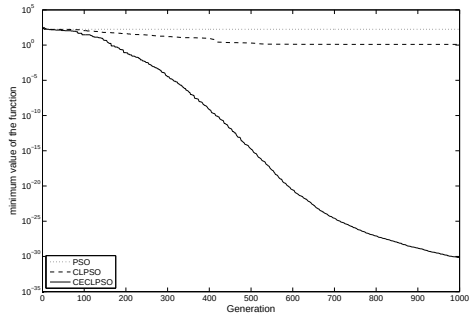


Figure 9. Convergence graph of function $f_9(x)$

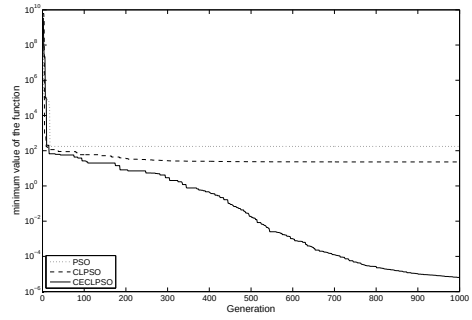


Figure 10. Convergence graph of function $f_{10}(x)$

benchmark functions of 50 dimensions are applied for optimization. Brief descriptions of each

algorithm along with CECLPSO are presented. The comparative results of the simulation are also presented. From the simulation, it is found that the CECLPSO outperforms the other said PSO variants in higher dimensional problems. In addition, to obtain better quality of solution, CECLPSO also overcome the premature convergence for higher dimensions. The strength of the proposed scheme lies in finding the global solution of the objective functions whose minima are regularly distributed. The proposed approach can not be taken as granted for all the types of the objective functions. Further work need to be done to overcome this drawback. This algorithm can be applied for delay optimization, molecular geometry optimization, placement and routing optimization in Very Large Scale Integrated circuit design.

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Table 1
Summary of results for function with dimension **50**

Functions	Algorithms	Best	Worst	Mean	Median	STD
f_1	PSO	2.85	3.38	3.19	3.20	1.17e-01
	CLPSO	7.80e-02	1.59	5.39e-01	5.06e-01	4.13e-01
	CECLPSO	2.66e-15	2.66e-15	**2.66e-15**	2.66e-15	**0**
f_2	PSO	2.12e+02	5.14e+2	3.40e+02	3.36e+02	6.57e+01
	CLPSO	5.47	2.05e+01	1.24e+01	1.21e+01	4.07
	CECLPSO	6.66e-01	6.66e-01	**6.66e-01**	6.66e-01	**2.82e-06**
f_3	PSO	1.72e-01	3.17e-01	2.41e-01	2.37e-01	3.738e-02
	CLPSO	4.86e-04	1.09e-02	2.76e-03	2.49e-03	2.19e-03
	CECLPSO	0	0	**0**	0	**0**
f_4	PSO	1.88	2.59	2.31	2.34	1.63e-01
	CLPSO	5.19e-03	4.37e-01	**6.86e-02**	3.24e-02	**8.69e-02**
	CECLPSO	2.78e-01	6.76e-01	4.61e-01	4.49e-01	1.17e-01
f_5	PSO	1.01e+02	3.18e+02	2.01e+02	1.88e+02	5.01e+01
	CLPSO	7.55e-02	4.07	9.96e-01	7.39e-01	8.35e-01
	CECLPSO	8.87e-45	1.01e-31	**3.36e-33**	2.24e-43	**1.84e-32**
f_6	PSO	3.47e+02	4.15e+02	3.84e+02	3.85e+02	1.57e+01
	CLPSO	2.73e+01	9.86e+01	5.91e+01	5.76e+01	**1.576e+01**
	CECLPSO	0	1.62e+02	**5.21e+01**	5.43e+01	5.14e+01
f_7	PSO	5.19e+02	7.93e+02	7.03e+02	7.07e+02	6.89e+01
	CLPSO	5.77e+01	2.03e+02	1.49e+02	1.62e+02	4.44e+01
	CECLPSO	4.75e+01	4.87e+01	**4.82e+01**	4.83e+01	**3.46e-01**
f_8	PSO	6.42	1.07e+01	8.34	8.36	1.05
	CLPSO	1.08e-02	3.18e-01	7.79e-02	5.16e-02	7.09e-02
	CECLPSO	8.42e-49	8.66e-47	**1.15e-47**	4.17e-48	**1.79e-47**
f_9	PSO	1.38e+02	2.35e+02	1.87e+02	1.86e+02	2.17e+01
	CLPSO	7.90e-02	5.73	1.30	9.74e-01	1.17
	CECLPSO	8.63e-48	1.00e-44	**8.67e-46**	3.56e-46	**1.85e-45**
f_{10}	PSO	1.18e+01	4.06e+02	1.44e+02	1.08e+02	1.09e+02
	CLPSO	5.31	4.46e+01	1.47e+01	1.19e+01	9.28
	CECLPSO	1.30e-05	1.06e-01	**1.76e-02**	4.17e-03	**2.78e-02**

Table 2
Benchmark Functions Definition

Name	Definition	Range
Ackley	$f_1(x)$=$20 + e^{-\frac{1}{5}\sqrt{\frac{1}{n}\sum_i (x_i)^2}} - e^{-\frac{1}{n}\sum_i^n cos(2\pi x_i)}$	[32.768,-32.768]
Dixon Price	$f_2(x) = (x_1 - 1)^2 + \sum_{i=2}^n i(2x_i^2 - xi - 1)^2$	[-10, 10]
Griewank	$f_3(x)$=$\sum_{i=1}^D \frac{x_i^2}{4000} - \prod_{i=1}^N cos\left(\frac{x_i}{\sqrt{i}}\right) + 1$	[-100, 100]
Levy	$f_4(x)$=$sin^2(\pi y_1) + \sum_{i=1}^{n-1}[(y_i - 1)^2$ $(1 + 10sin^2(\pi y_i + 1))]$ $+(y_n - 1)^2\left(1 + 10sin^2(2\pi y_n)\right)$, where, $y_i = 1 + \frac{x_i - 1}{4}, i = 1, 2, \cdots n$	[-10, 10]
Powel	$f_5(x)$=$\sum_{i=1}^{n/4}\left(x_{4i-3} + 10x_{4i-2}\right)^2 + 5(x_{4i-1} - x_{4i})^2$ $+(x_{4i-2} - x_{4i-1})^4 + 10(x_{4i-3} - x_{4i})^4$	[-4 5]
Rastrigin	$f_6(x)$=$\sum_{i=1}^D \left(x_i^2 - 10cos(2\pi x_i) + 10\right)$	[-5.12 5.12]
Rosenbrock	$f_7(x)$=$\sum_{i=1}^{D-1}\left[100\left(x_i^2 - x_{i+1}\right)^2 + (x_i - 1)^2\right]$	[-100 100]
Sum Square	$f_8(x)$=$\sum_{i=1}^D ix_i^2$	[-10, 10]
Zakharov	$f_9(x)$=$\sum_{i=1}^n x_i^2 + \left(\sum_{i=1}^n 0.5ix_i\right)^2 + \left(\sum_{i=1}^n 0.5ix_i\right)^4$	[-5, 10]

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INITIALIZATION OF ROBOTIC FORMATIONS USING DISCRETE PARTICLE SWARM OPTIMIZATION

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ABSTRACT

In this paper, a Discrete Particle Swarm Optimization (DPSO) technique is applied as an optimal motion planning strategy for the initialization of mobile robots to establish some geometrical patterns or formations. Firstly, an optimal assignment of location and orientation for each robot in the formation is performed. For this, a total travelling cost is defined, involving the angular and translational movement by all robots from their initial positions in the workspace to their goal positions. The objective is then to determine the position for each robot in the formation in order to minimize the cost function to form a predefined shape. Once each robot has been assigned with a desired position, a search scheme is implemented to obtain a collision free trajectory for each robot to establish the formation. Simulation results are presented to illustrate the validity of the proposed approach.

KEY WORDS

Motion Planning, Robotic Formation Initialization, Position Assignment, Discrete Particle Swarm Optimization.

1. INTRODUCTION

Robotic formation is defined as the coordination of a group of mobile robots to get into and maintain a desired pattern with a certain geometric shape. Multi-robot coordination has recently received a considerable interest as various applications can be performed faster and more efficiently with multiple robots than with single robots operating independently. Applications requiring multiple robot coordination include mine sweeping [1], moving large objects in a construction site or military scouts [2-4], where each robot needs to be in a particular position corresponding to its sensing capacity or geometrical advantage to perform a given cooperative task. Such problems as initializing the formation, maintaining the formation configuration, avoiding static or moving obstacles in the workspace, and changing formation shapes to fulfil a specific task or to deal with obstacles remain important issues in robotic formation control [5].

Several approaches to solve one or more of the above subtasks can be found in the literature [6-9]. In [10], a directed potential field method was used for motion coordination of robots moving in formations, however, the inherent drawback of potential field method in the cases of local optima was not mentioned. An architecture for robotic formation control was proposed in [5] to solve the four main issues mentioned above. The authors focused on the problem of how to assign the most suitable position for each robot in the formation using a bounded depth-first search with a pruning algorithm to minimize a cost function compromising the level of a follower robot in a formation, the distance and heading deviation of a follower with respect to its leader robot. The search is distributed over every robot in the formation and the result with the lowest cost is

chosen. This method is somewhat similar to the work proposed by [11], in which a robot in the group plans its own path independently and a D* search in a coordination diagram is performed to obtain the minimum cost trajectory for each robot in a multi-robot system. Obviously, a search process for this purpose would require a suitable optimisation technique.

Particle Swarm Optimization (PSO), originally developed by Kennedy and Eberhart [12], has proven to be of great potential for optimization applications and has been used successfully in robotics. For example, PSO was used for target searching problems with single and multiple target cases [13]. In [14], a modified PSO algorithm was introduced to find an optimal path for mobile robots. In construction automation, a PSO-based has been recently proposed for the coordination of a group of robotic vehicles [15]. Dealing in a similar application, the Generalized Discrete Particle Swarm Optimization (DPSO), proposed by Clerc [16], was applied for the Travelling Salesman Problem. The author pointed out that DPSO is easily implemented for discrete or combinational problems, particularly when a sufficiently good specialized algorithm is unavailable.

This paper addresses the problem of how to initialize a robotic formation by seeking an optimal position assignment for each robot in the formation. Each robot will be designated a desired position while minimizing the total cost which includes the translational and angular movement of all robots in the formation. The workspace is assumed to be obstacle-free so the shortest path for each robot from its initial position to its assigned position will be a straight line connecting the two positions. As each robot moves to its goal, collision between two or more robots may occur. We propose a search scheme to construct the velocity profile for those robots which may potentially collide with the others.

The rest of the paper is organized as follows. In Section 2, a brief review of DPSO is presented. The proposed robotic formation initialization approach is described in Section 3. Section 4 gives some simulation results to demonstrate the validity of the approach. A conclusion is given in Section 5 of the paper.

2. DISCRETE PARTICLE SWARM OPTIMIZATION

In Particle Swarm Optimization, a set of moving particles are initially thrown into the search space. Each particle, having a position and a velocity, knows its own position and the fitness function to evaluate its solution quality. Each particle randomly searches through the problem space by updating its own memory with its position and the social information gathered from other particles. At each time step, the movement of a particle is a compromise of three behaviours: to move randomly (its own way), to go towards its best previous position (memory), and to go towards its neighbour (global) best position. This evolutionary selection is described by the following equations for the i^{th} particle:

$$\begin{cases} v_{i,new} = c_1 \otimes v_{i,old} + c_2 \otimes \left(p_{i,b} - p_{i,old}\right) + c_3 \otimes \left(g_b - p_{i,old}\right) \\ p_{i,new} = p_{i,old} \oplus v_{i,new} \end{cases} \tag{1}$$

where

$v_{i,new}$	New velocity calculated for the i^{th} particle
$v_{i,old}$	Velocity of the i^{th} particle from the previous iteration
$p_{i,new}$	New position calculated for the i^{th} particle
$p_{i,old}$	Position of the i^{th} particle from the previous iteration
$p_{i,b}$	Best position of the i^{th} particle so far
g_b	Best position of from the neighbour so far
c_1, c_2, c_3	Social/cognitive confidence coefficients

The PSO algorithm described above is known as traditional PSO and works well only in continuous domains. This is a limitation of the classical PSO because many applications are set in a space featuring discrete variables. Naturally, Discrete Particle Swarm Optimization (DPSO) is developed to tackle those discrete optimization problems. It differs from the traditional PSO in the sense that its particles do not represent points in the n-dimensional Euclidean space [17]. In this paper, it represents, in a discrete nature, a combination of selected position assignments for mobile robots in a formation. Equation (1) is also used to update

particle's velocity and position in the DPSO. The particle position and velocity encoding varies from one specific problem to another and will be presented in Section 3 for the case of position assignment.

3. ROBOTIC FORMATION INITIALIZATION APPROACH

3.1 Premises and Problem Statement

The focus here is on the optimal position assignment and trajectory generation for robots in a desired formation, other issues such as path planning, choice of the leader robot in a formation or motion control are beyond the scope of this paper. We assume that the planner knows the desired position of a formation and the environment for initialization is obstacle-free. Each robot is assumed to move at constant speeds and be able to switch instantaneously between a fixed speed and halting, which is typical in multi-robot motion planing [11]. Therefore, the shortest path for a robot would be a straight line connecting its initial position and its desired position in the formation. The formation initialization problem for N robots is now defined as follows: *Given the position of the leader robot and a desired formation configuration, assign the desired position for each robot in the group and find a set of velocity profiles for each robot* $R_i (i = 1,..., N-1)$ *to move from its initial position to its desired position without colliding with each other, while minimizing the total time for all robots to establish the formation.*

3.2 Formation Initialization Algorithm

We divide the problem into two sub problems. Firstly, DPSO is applied to find the optimal position assignment for each robot. Each robot is assigned a desired position in a formation so that total time required by all robots to form the formation is minimized. Once each robot has known its assigned position, the next step is to perform a geometric checking to find a priority scheme by which a robot has to wait for others in the case of a potential collision with another robot and the total waiting time for all robots will be minimized.

3.2.1 Position Assignment

Let us consider N robots initially scattering in the workplace. One robot has been chosen to be the reference robot and is called the "leader robot" while the rest are called follower robots in this paper. The selection of the leader robot may be based on its geographical advantage in the whole group or its powerful sensing capacity. From the initial position of the selected leader robot together with the required formation configuration, desired positions of all follower robots in the formation are calculated. If there are N robots, including the leader, to enter a formation in which each desired position in the formation is indexed as $P_i(x_i, y_i, \theta_i), i = 1..N-1$, or just P_i for convenience, and each robot excluding the leader has a unique identification (ID) as $R_1,..., R_{N-1}$ or just $1, ..., N-1$ then each particle position and velocity are encoded as follows.

- Particle position $p_i = (x_1, x_2,..., x_{N-1})$, with $x_j \in \{1,.., N-1\}$ means that robot R_{x_i} is assigned to the desired position P_{x_i} in the formation.

Objective function

As stated above, the criteria for the position assignment problem is to minimize the total distance traversed by all robots to form the formation. To ease the computational burden of the planner as well as the implementation complexity in trajectory tracking for each robot, the trajectory of each robot when moving from an initial position to its desired position is separated into three phases. They are: (i) spinning on its wheels to align with the straight line connecting its initial position to its desired position; (ii) following that line, and (iii) spinning on its wheels to align with the formation orientation. Suppose the i^{th} follower robot does not have to wait for other robots in a potential collision or there is no propensity of collision, then the time needed to reach its goal is

$$T_i = \omega_i^{-1}\alpha_{i,1} + \omega_i^{-1}\alpha_{i,2} + v_i^{-1}d_i, \qquad (2)$$

where $\alpha_{i,1}$, $\alpha_{i,2}$ and d_i are respectively angular and translational displacement corresponding to each phase. The objective function is chosen as:

$$\min_{v_i,\ \omega_i} (F = \sum_{i=1}^{N-1} T_i) \quad s.t. \text{ safety} \tag{3}$$

The actual total time executed by a follower robot to reach a desired position may be different from (2) as it may have to stop and wait for other robots if inter-vehicle collision is to happen. As each robot's angular $(\alpha_{i,1} + \alpha_{i,2})$ and translational (d_i) movement are assigned by the desired formation shape, a solution found with a minimum cost defined by (3) will guarantee that the position assignment is time-optimal subject to the safety condition of inter-robot collision avoidance, which will be described in the next section.

3.2.2 Motion Planning

As mentioned, the cost function used in DPSO algorithm given in (3) should be subject to the collision-free condition. This constraint is resolved in this paper via a motion planner to construct a suitable trajectory for each robot where its safety will be preserved. For the safety purpose, the physical robot is located as a circle with radius $r_{safe} = r + r_{margin}$, where r is the distance from the center of the robot to the its furthest point and r_{margin} is the marginal clearance around it [18]. With the segmentation of a robot's trajectory corresponding to three phases as stated above, the boundary of a robot path will be rectangular which facilitates the geometrical collision checking.

To safely reach a target for a robot in the group, a quick geometrical check is performed to identify robots which potentially collide with each other. Those robots whose paths do not geometrically collide with others will be excluded from the search operation and their velocity profiles are constructed straightforwardly. For those robots whose geometrical paths cross the other paths may or may not collide with each, depending on whether or not they reach the same point at the same time, their velocity profiles are obtained from the search by adopting further the following inter-vehicle collision avoidance strategy:

- For robot R_i, calculate the time instant and duration it crosses the other robots' paths as $CT_i = [(t_0^1,\ t_1^1, index_1), (t_0^2,\ t_1^2, index_2), \cdots, (t_0^j,\ t_1^j, index_j)]$ which means robot R_i crosses and occupies the path of robot R_{index_j} during $(t_0^j,\ t_1^j)$. Once a robot crosses another robot's path, it is included in the inter-vehicle collision avoidance checking even if it does not reach the crossing point at the same time with the other robot. Thus, CT_i will change over time as explained later.

- The search result for robot R_i is of the form $VP_i = [b_1, b_2, \cdots, b_{M_i}]$, where $b_i \in \{0, 1\}$ and M_i is the number of time steps in the search outcome for robot R_i. This will depend on the length of the robot path, robot velocity, and the duration of each time step. Robot R_i will follow its planned path with a constant velocity during the i^{th} time slot if $b_i = 1$; otherwise, it stops. When $b_i = 1$, the velocity of robot R_i may be $(v_i = 0, \omega_i = const)$ if it is spinning on wheels, or $(v_i = const, \omega_i = 0)$ if it is following the straight line to its desired position.

- Collision between any two robots, if occurs, will take place only one time due to the feature of a robot path. Hence, once the collision issue has been resolved, these two robots are collision-free with each other so either one will be released from the safety check with respect to the other. If a robot has no more potential collision with others, it will be released from the inter-robot collision checking procedure and it will safely follow its path.

- Deadlock may occur if robot R_i crosses the target of robot R_j [15]. In order to avoid this deadlock, R_j must wait until R_i passes its target.

- If a robot reaches the crossing area before its counter-part robot and no deadlock occurs when crossing the area first, then it will have a higher priority than its counter-part. If deadlock occurs, it has to wait for its counter-part to cross first and therefore, acting in a lower priority.

- At each time step i^{th}, the current time is compared with the time in CT_i:

1. If R_i does not reach any crossing area, set $b_i = 1$.

2. If R_i is at a crossing area:

   2.1 If deadlock occurs when it moves, set $b_i = 0$.

   2.2 If no deadlock occurs and its counter- part has not reached this crossing area, set $b_i = 1$

   2.3 If no deadlock occurs and its counter-part has reached this crossing area:

   - If it has entered this area before its counter-part then it will continue moving, i.e., set, $b_i = 1$.
   - If a counter-part has entered this area before the considered robot R_i , then check the collision potential between the two robots. If both of them move to the next step, then set b_i accordingly, i.e., $b_i = 1$ if no collision exists and $b_i = 0$ otherwise.
   - If R_i has passed the crossing area, then release R_i and its counter-part from the checking procedure in future steps.

After all the search results have been found, desired velocity profiles or safe trajectories for all robots in the formation will be constructed straightforwardly.

4. SIMULATION RESULTS

The proposed method for robotic formation initialization using DPSO and the behavioural collision avoidance strategy is applied to simulations for different type of formation configurations with different number of robots. Due to limited space, the simulation results for a case of 9 robots to form a line formation are presented.

Figure 1a through 1d show the snapshots for robot locations over time. The robots from left to right and top to bottom are the leader robot, the initial location of follower robots $R_1, R_4, R_6, R_5, R_7, R_8,$ and R_2, respectively. The proposed algorithm gives the best position as $P_{best} = [1, 4, 3, 6, 5, 8, 7, 2]$.

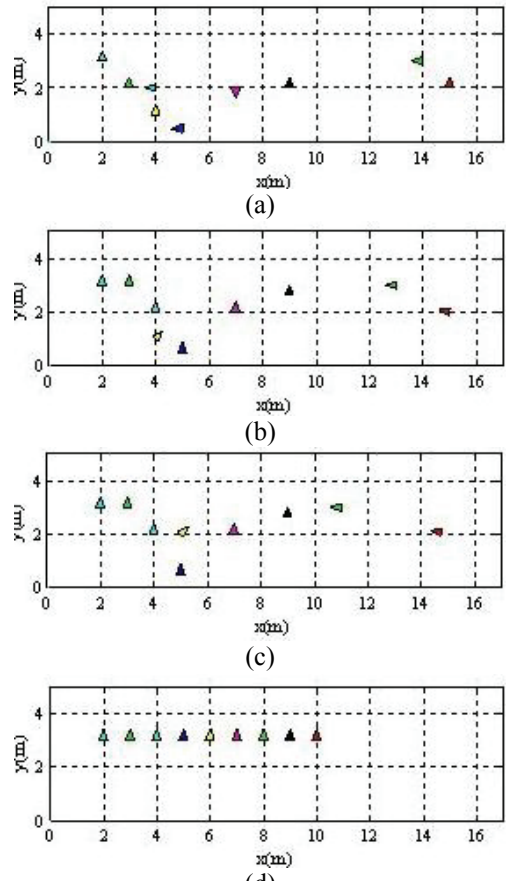


Figure 1. Example of Nine Robots to Form a Line Formation. Snapshots of the Formation Over Time.

5. CONCLUSION

A discrete particle swarm optimization (DPSO) algorithm has been proposed for scheduling optimally the position ass ignment to initialize a formation of vehicles, which can be deployed for construction automation purposes. For the sake of simulation, the fitness function to implement DPSO comprises the total time required for all vehicles to establish the formation, subject to the collision avoidance condition. Simulation results are included to verify the approach effectiveness. Inpractice, further criteria such as sensing capacity and geometrical advantages can also be incorporated in this multi-objective optimization technique.

6. ACKNOWLEDGMENTS

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MR DAMPER OPTIMAL PLACEMENT FOR SEMI-ACTIVE CONTROL OF BUILDINGS USING AN EFFICIENT MULTI-OBJECTIVE BINARY GENETIC ALGORITHM

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ABSTRACT

In order to ensure the survival of building structures during earthquake periods, induced vibrations have to be mitigated. In this regard, semi-active control of smart structures using magneto-rheological dampers is becoming an emerging technology. Improvements on vibration reduction are foreshadowed when the dampers are installed at critical locations on the building structure. In this paper, the placement of dampers is cast as a multi-objective optimization problem in the sense of minimum resultant vibration magnitudes and with a minimum number of dampers. A binary-coded genetic algorithm is employed as the optimizer owing to its computational flexibility and high performance. Simulation results are included to illustrate the effectiveness of the proposed approach on a high-rise building model subject to benchmark earthquake records.

KEYWORDS

Building Control, Damper Placement, Genetic Algorithm, Multi-Objective Optimization

1. INTRODUCTION

Casualties during earthquake periods could be very extensive. Particularly, in urban areas, loss of human lives and economic costs paid are mainly caused by collapsing of building structures due to induced vibrations. Intuitively, buildings have to be built with sufficient resistances to vibrations but there is always a limit in the affordable capitals invested in their constructions. Control schemes aimed at vibration reductions [1], hence, are becoming attractive alternative approaches. Practically, there are a number of devices available such as tune mass dampers [2]; however, power sources may not be available during earthquake periods. To this end, dampers with controllable characteristics, for example, the magneto-rheological (MR) dampers are widely adopted in this problem domain [3]. Furthermore, to reduce system complexity, power consumption and to ensure satisfactory performances, it is important to place the dampers in their critical locations in the building.

The importance of damper locations affecting the vibration characteristics of structures has been noted more than a decade ago [4], where a multi-body system was used as a study example. Vibration reduction in building structures can be regarded as the problem of maximizing the efficiency taking into account the energy dissipated in dampers [5]. Obviously, minimum vibration magnitudes are crucial criteria for judging the effectiveness [6]. Therefore, placing the dampers can be naturally tackled as an optimization process and was addressed in [7] where the use of steepest direction search might call for analytical system models. Alternatively, heuristic approaches [8] such as Tabu search or simulated annealing have been attempted.

On the other hand, established techniques in the evolutionary computation area have been

recognised as attractive candidates in tackling the damper placement problem considered. A genetic algorithm (GA) is used in [9] to obtain optimal placements of sensors/actuators on civil structures. The work reported in [10], considering the damper location problem also used the GA in conjunction with criteria derived from the system transfer function. The GA with a weighted-sum approach was proposed in [11] for optimal locations in a civil structure where dampers are installed. However, assignment of proper important weights is generally difficult.

While evolutionary computation techniques are effective strategies to solve the damper placement problem, optimization for multiple objectives has not been fully emphasized. In this direction, the GA operating as a multi-objective optimizer has recently appeared in the literature [12], where the vibration magnitude and the number of dampers used are adopted as objective functions.

The remainder of the paper is organized as follows. In Section 2, the semi-active control problem for smart structures with MR dampers is briefly presented. Section 3 reviews the use of binary-coded GA in the multi-objective optimization paradigm. The optimal placement of dampers is considered in Section 4 and preliminary results are given in Section 5. In Section 6, a conclusion is drawn.

2. MR-DAMPER CIVIL STRUCTURES

The civil structure considered is a multi-storey building consisting, for simplicity, of an aggregation of single degree-of-freedom bays. The building is subject to simulated earthquake excitations, e.g., from a shake-table facility, and magneto-rheological (MR) dampers are to be installed to alleviate the vibrations induced on the floors.

2.1 System Description

Consider the *n*-storey building structure shown in Fig.1, the equation of motion can be expressed as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{\Gamma}\mathbf{f} + \mathbf{M}\mathbf{\Lambda}\ddot{x}_g, \tag{1}$$

where $\mathbf{x}$ is the floor displacement vector, $\mathbf{M}, \mathbf{C}, \mathbf{K}$ are the mass, damping and stiffness matrices, $\mathbf{\Gamma}, \mathbf{\Lambda}$ are the distribution vectors for the damper force $\mathbf{f}$ and ground acceleration, $\ddot{x}_g$. An augmented system state equation is further formulated as

$$\dot{\mathbf{z}} = \mathbf{A}\mathbf{z} + \mathbf{B}\mathbf{u} + \mathbf{E}, \tag{2}$$

where $\mathbf{z} = [\mathbf{x}^T \ \dot{\mathbf{x}}^T]^T$ is the state vector,

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{\Gamma} \end{bmatrix}, \tag{3}$$

are the system and gain matrices, and earthquake induced disturbance is given by $\mathbf{E}$. The smart structure control $\mathbf{u}$ may be via the damper force $\mathbf{f}(t)$, or by applying directly appropriate current $\mathbf{i}(t)$ to pairs of MR dampers set in a differential configuration, as shown in Fig. 1, to cancel out the offset forces. The control development has been described in [13].

2.2 Optimal Damper Placement— A Rationale

The response of the building structure, under the effect of random earthquake excitation, largely depends on the system matrix $\mathbf{A}$ and the control effort $\mathbf{u}$. In fact, installation of the MR dampers will affect the system matrix elements via its lumped parameters on stiffness $\mathbf{K}$ and viscous damping $\mathbf{C}$. Furthermore, in direct control, the influence of the current input would also give way to the parametric dependence of the control gain matrix $\mathbf{B}$, whereby a zero entry is related to the absence of a damper pair installed at the corresponding storey. The control goals require therefore not only robustness and feasibility of the system but also the satisfaction of seismic response performance in an economic manner. To achieve these goals, a multi-objective optimization approach is proposed as in the following section.

3. MULTI-OBJECTIVE GENETIC ALGORITHM

In order to achieve optimum for both the number of dampers used and for the suppression of quake-induced vibrations, the control problem is cast as an optimization process for which several approaches that can be applicable. Here, for the sake of simplicity, flexibility and good performance, a multi-objective binary-coded GA is used.

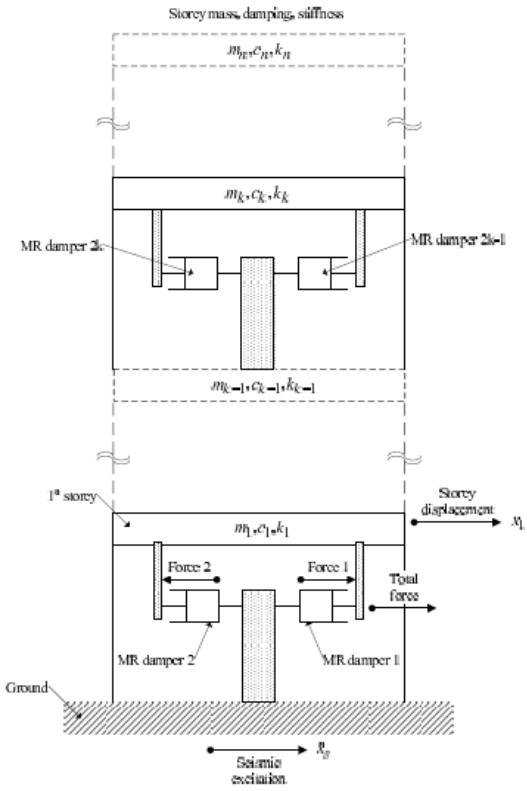


Figure 1 Multi-Storey Building Under Control

3.1 Binary-Coded Genetic Algorithm

Genetic algorithms are search routines inspired by the evolution of living species. In the course of evolution, descendants inherit favourable genetic ingredients from their ascendants such that the survivability of the whole population increases over generations. When using the principle of "survival of the fittest" to optimization algorithms, chromosomes of living organisms are coded in binary strings which represent potential solutions to the problem, see Fig. 2.

The quality of the solution to the problem is embedded as a fitness value assigned to each chromosome. A near-optimal solution is obtained by manipulating the population using genetic operators including *selection*, *crossover* and *mutation*. At the first generation (iteration) binary strings are generated in random to cover the solution space.

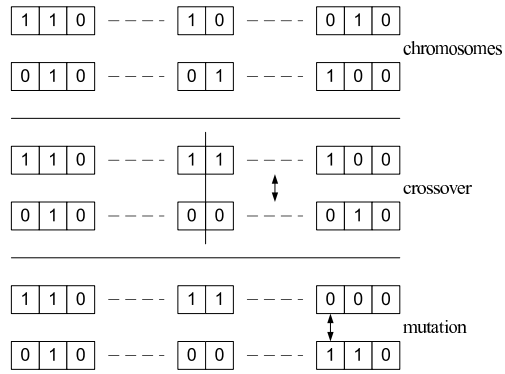


Figure 2 Operations of Genetic Algorithm

Their objective functions are evaluated and normalized to give the corresponding fitness. The chromosomes are selected to the next generation according to their fitness. A pair of chromosomes is then randomly picked and part of the string is exchanged by the crossover operator. Before evaluating the fitness, a random bit is flipped in the mutation process. The process is repeated until the number of generations reaches a pre-specified count.

3.2 Multi-Objective Genetic Algorithm

The problem of damper placement is concerned with obtaining minimum storey vibrations while using a minimum number of dampers. Without much *a priori* knowledge on control schemes, our intention is to formulate the damper placement as a multi-objective optimization problem.

The evaluation of the chromosome fitness has to be catered for this requirement. The objectives can be augmented into a single fitness by the use of importance weights. Although commonly-used in optimization, there has not been a generic methodology for the choice of weights available in the relevant literature.

In the context of evolutionary computation, several approaches have been proposed for this kind of optimization with genetic algorithms [12], including vector evaluated GA (VEGA) and fitness sharing (FSGA). In VEGA, sub-populations are used for evaluating a single objective and then combined by the selection operator. On the other hand, FSGA modifies the fitness by sectoring the objective-space. The fitness of chromosomes in

close objective-space vicinities is reduced to promote searching for better solutions.

In this work, the principle of Pareto front is applied making use of the fact that it does not need to determine the required sub-populations. In essence, chromosomes at the frontier of the fitness landscape are assigned with higher ranks. The ranking is defined as

$$R_i = \sum_{m=1}^{M} N(f_i^m < f_{j\neq i}^m), M = 2 \quad (4)$$

where i is the chromosome index, m is the objective index, $N(.)$ is the operator that gives the number of satisfactions for condition inside the bracket.

4. OPTIMAL DAMPER PLACEMENT

The damping devices used are briefly presented in this section. Then a optimization procedure implemented with GA is developed for placing them in the civil structure.

4.1 Damper Model

The MR damper used in this study is a LORD RD-1005-3 model. The damper force generated is a function of the compression/extension displacement and velocity, described by a static hysteresis model as given in [14]:

$$\begin{aligned} f_{di} &= c_d \dot{x}_{di} + k_d x_{di} + \alpha z_d \\ z_d &= \tanh(\beta \dot{x}_{di} + \delta \text{sign}(x_{di})), \end{aligned} \quad (5)$$

to represent the non-linear force/displacement relationship, where z_d is the hysteretic variable, and

$$x_{di} = x_{i+1} - x_i, \quad (6)$$

is the inter-storey displacement. The equation of motion can be written, for an individual storey, as

$$\begin{aligned} &m\ddot{x}_i + c\dot{x}_i + kx_i = -f_{d\,i} + m\ddot{x}_g \\ &= -c_d \dot{x}_{i+1} + c_d \dot{x}_i - k_d x_{i+1} + k_d x_i - \alpha z_d + m\ddot{x}_g, \end{aligned} \quad (6)$$

or

$$\begin{aligned} &m\ddot{x}_i + (c - c_d)\dot{x}_i + (k - k_d)x_i \\ &= -c_d \dot{x}_{i+1} - k_d x_{i+1} - \alpha z_d + m\ddot{x}_g, \end{aligned} \quad (7)$$

which clearly shows the modification of the storey response when a damper is installed.

4.2 GA Modified Gain Matrix

The gain matrix $\mathbf{B}$ given in (2) contains an upper $n \times n$ zero matrix corresponding to the number of storeys. The lower part $\mathbf{\Gamma}$ is an identity matrix also of $n \times n$ scaled inversely by the mass of the storey. If a damper is not installed, the corresponding element of the matrix $\mathbf{\Gamma}$ becomes zero instead. This special matrix structure naturally poses the optimization problem in the domain of a binary-coded genetic algorithm (BCGA) optimization. Here, the chromosome depicted in Fig. 2 is used to represent the diagonal elements in matrix $\mathbf{\Gamma}$ and will be manipulated through generations in the algorithm.

4.3 Optimization Problem

The goal of reducing the root-mean-square vibration magnitudes induced on the building and the use of a minimum number of dampers together constitutes to a multi-objective optimization (minimization) problem. It is stated as follows:

Minimize:	Storey RMS displacement AND Number of dampers
Subject to:	Supplied damper current $0 \le i_d \le i_{d,\max}$.

A chromosome in GA is encoded as a string of 1's and 0's, for example

$$\mathbf{C}_i = [0,\cdots,1,\cdots,1]^T, i = 1,\cdots P, \quad (8)$$

where the length of the i-th chromosome corresponds to the number of storeys n with entries 1 corresponding to the damper-installed storey, and P is the number of chromosomes to form a population.

The fitness of one of the objectives, the minimization of number of dampers used is

$$f_i^d = \sum_{k=1}^{n} C_{i,k}, \quad (9)$$

where k is the index for the gene inside a chromosome. The other objective fitness, the root-mean-squared (RMS) displacement is calculated as

$$\tilde{f}_i^r = \sqrt{\frac{1}{N}\sum_{t=1}^{\tau}(x_i^t)^2}, \; f_i^r = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(\tilde{f}_j^r)^2} \quad (10)$$

here, N is the number of displacement time series x_i^t, and τ is the maximum earthquake time considered. Finally, the overall Pareto-ranked

fitness is given as in (4), where for the sake of simplicity M is set to 2 in this work. The final solution is given by the chromosome with highest rank in the terminating generation.

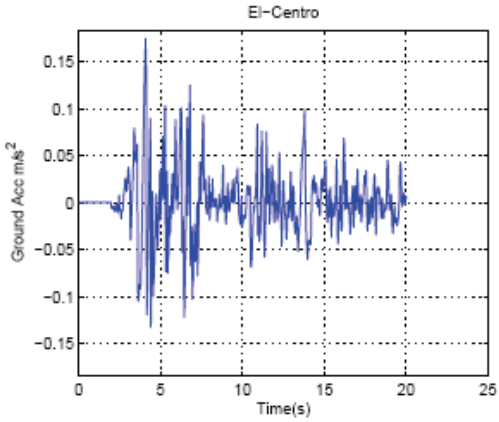


Figure 3 El-Centro Earthquake Record

5. RESULTS

Simulation studies are conducted using the scaled down (50%) benchmark El-Centro earthquake record, Fig. 3, for 20 seconds. The building model is designed such that the natural vibration mode frequencies are ranged from 1Hz to 23Hz for a 20-storey building. The masses and stiffness are assumed equal in every floor and a damping ratio of 2%, also for every floor, is assumed.

5.1 Passive-off MR Dampers

In this case, dampers are supplied with zero currents (in passive-off mode) and the resultant RMS displacements are depicted in Fig. 4.

The dotted line represents the displacement when no dampers are installed and the building structure is in the so-called free vibration. The case with dampers installed at all the stores are given by the solid line where dots indicate the floor level.

The effect of the use of a reduced number of dampers, 8 damper pairs in this case, is illustrated by the dark solid line with squares indicating the stores where dampers are employed. It is shown that the use of a smaller number of dampers is acceptable with the satisfactory resultant displacement.

5.2 Passive-on MR Dampers

Two cases are considered when the dampers are supplied with a moderate current (1A) and the maximum current (2A). Their corresponding effectiveness is illustrated as below.

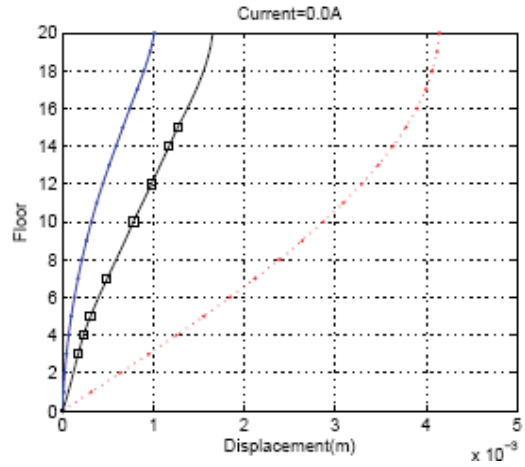


Figure 4 RMS Displacements from Passive-off test (dash dot: no damper, solid dot: max. no. of dampers used, solid square: optimal placed dampers)

5.2.1 Moderate supply current

Figure 5 shows the RMS displacements under this test scenario. As illustrated and with the use of 9 damper pairs under the effect of a moderate supply current, the response is slightly better than the full-installation configuration with passive-off dampers.

It is believed that due to the modified overall structural stiffness, with the installation of dampers at critical points, resonant characteristics are altered and vibrations have been reduced. On the other hand, full-installation may result in a too large rigidity where vibration energies have not been completely absorbed.

5.2.2 Maximum supply current

Simulation results are illustrated in Fig. 6. It is noted that the vibration of full-installed configuration is largest among the three cases. This could be explained that the structural rigidity is further increased and results in insufficient vibration absorption. However, the displacement is smaller than the free-vibration case.

With the use of a reduced number of dampers, 3 damper pairs used in this case, the response is comparable to the previous case with a moderate supply current. It should be noted, that only a few dampers could be used where larger currents supplied increases the capability of vibration

absorption. To this end, simultaneous achievement of both optimization objectives is evident.

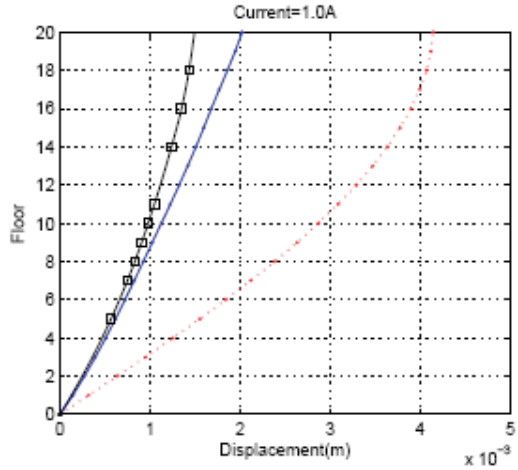


Figure 5 RMS Displacements from Passive-on Test, Moderate Supply Current

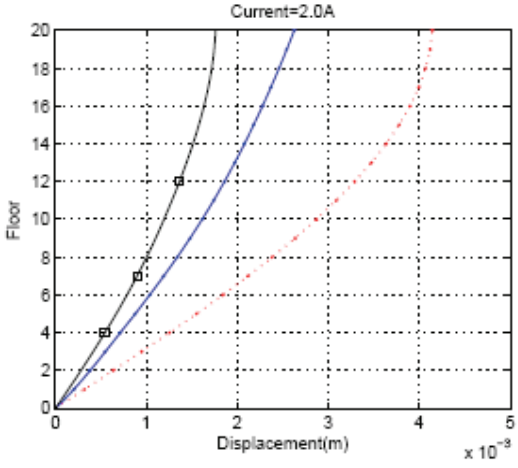


Figure 6 RMS Displacements from Passive-on Test, Maximum Supply Current

6. CONCLUSION

This paper has addressed the problem of optimal placement of semi-active resources in the control of civil structures against earthquake excitations. The problem is tackled from a multi-objective optimization perspective where a binary-coded genetic algorithm is used as the optimizer to obtain near-optimum locations to install the MR dampers. The use of the BCGA together with the Pareto-front approach is effective in this problem domain, in which the objectives for the use of resources and performance are simultaneously achieved. Satisfactory results using the El-Centro benchmark earthquake records have verified the proposed approach. Future work will be directed towards the incorporation of controllers on the damper supply currents, together with an increase in the number of objectives, in an integrated manner to address optimality in the smart structure technology.

7. ACKNOWLEDGMENT

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EFFECT OF CROSS OVER OPERATOR IN GENETIC ALGORITHMS ON ANTICIPATORY SCHEDULING

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ABSTRACT

Disk schedulers in current operating systems schedule a request as soon as the previous request has been completed. In many common applications disk read requests are issued synchronously with short period between them In this case, the scheduler switches to a request from another process with the assumption that the last process has no more requests. This condition is called deceptive idleness. It can be overcome by anticipatory disk scheduling framework, which introduces a short, controlled delay period, during which the disk scheduler waits for additional requests to arrive from the process that issued the last serviced request.

Genetic algorithms, powerful and broadly applicable optimization techniques and the most widely known types of evolutionary computation methods can be used for optimizing the anticipatory scheduling. In this paper, we propose to use the cross over operators while tuning the anticipatory scheduling with Genetic algorithms. In general, a cross over operator is regarded as a main genetic operator and the performance of genetic algorithms depends to a great extent on the performance of the cross over operator used. We make the study on Linux Operating Systems kernel 2.6.18. We use various cross over operators and make a comparison on the performance of anticipatory scheduling.

KEYWORDS

Anticipatory Scheduling, Genetic Algorithms, Crossover Operator

1. INTRODUCTION

Disk schedulers select a request for service as soon as (or before) the previous request has completed. Now consider processes issuing disk requests synchronously. After one request has finished, each process issues a new request. So, there is one request at any time. The scheduler assumes that there is no further request from the last process. It selects a request from other process. The scheduler is not able to consecutively service more than one request from the processes. This is the condition called as deceptive idleness. If the data requested is sequential, this problem is common. The scheduler has to reorder the requests correctly and hence there is performance degradation.

The anticipatory disk scheduling framework introduces a short, delay period in such a way that the scheduler waits for additional requests to be issued by the process, which issued the last serviced request. Utilization is improved since the scheduler is able to service more than one request from the same process. The anticipatory scheduling framework is an adaptive heuristics based on a simple cost-benefit analysis [1].

Genetic Algorithms (GA) are stochastic search algorithms, which borrow some concepts from nature. GA maintain a population pool of

candidate solutions called strings or chromosomes. Each chromosome is a collection of building blocks called genes. A fitness value is associated with each chromosome. A user-defined function called fitness function determines the fitness value. The function returns a magnitude that is proportional to the candidate solution‘s suitably and/or optimality. At the start of the algorithm, an initial population is generated randomly or according to some rules. The reproduction operator selects chromosomes from the population to be parents for a new chromosome. The crossover operator oversees the mating process of two chromosomes. It decides what genetic material from each parent is passed on to the child chromosome. The mutation operator takes each chromosome in the offspring pool and randomly changes part of its contents. Thus each new generation of chromosomes are formed by the action of genetic operators on the older population. The chromosomes are compared via their fitness value to derive a new population, where the weaker chromosomes may be eliminated [2].

The work outlined in this paper involves optimizing the read and write requests in anticipatory scheduling using genetic Algorithms and preliminary results are provided. Since the source code is open, we implement the Genetic Algorithms on anticipatory scheduling as external modules in Linux Kernel 2.6.18. We use the results of the study show that significant improvement in performance is possible using Genetic Algorithms for scheduling.

2. OVERVIEW OF ANTICIPATORY SCHEDULING

In disk scheduling, the following three conditions cause deceptive idleness: (1) multiple disk-intensive applications concurrently issuing synchronous disk requests, (2) the intrinsic non-preemptible nature of disk requests, and (3) a work-conserving disk scheduler, which schedules a request immediately upon completion of the previous request. After the request completes, the framework potentially waits briefly for additional requests to arrive, before dispatching a new request to the disk. Applications, which quickly generate another request, can do so before the scheduler takes its decision. Here, deceptive idleness is thus avoided. The fact that the disk remains idle during this short period is not necessarily detrimental to performance. In practice, the framework waits for the shortest period of time over which it expects, in high probability, for the benefits of waiting to outweigh the costs of keeping the disk idle [1].

The anticipatory scheduling framework consists of three components: (1) The original disk scheduler, which implements the scheduling policy and is unaware of anticipatory scheduling; (2) a scheduler-independent *anticipation core*; and, (3) adaptive scheduler-specific *anticipation heuristics* for seek reducing and proportional-share schedulers.

Figure 1 depicts the architecture of the framework. The anticipation core implements the generic logic and timing mechanisms for waiting, and relies on the anticipation heuristic to decide if and how long to wait. This heuristic is implemented separately for each scheduler, and has access to the internal state of the scheduler. To apply anticipatory scheduling to a new scheduling policy, one merely has to implement an appropriate anticipation heuristic.

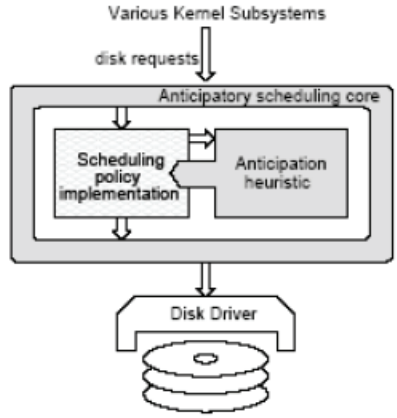


Figure 1 Anticipatory Scheduling Framework

3. GENETIC ALGORITHMS METHODOLOGY

GAs are a population-based model, which uses selection and recombination operators to generate new sample points in the solution space. GAs encode a potential solution to a specific problem on a chromosome-like data structure and applies

recombination operators to these structures in a manner that preserves critical information. Reproduction opportunities are applied in such a way that those chromosomes representing a better solution to the target problem are given more chances to reproduce than chromosomes with poorer solutions. GAs are a promising heuristic approach to locate nearoptimal solutions in large search spaces.

There are three phenotypes that are just fitness measures. The fitness routine looks at the delta of number of I/O operations completed during a child's lifetime. This fitness routine helps balance out the idea of pure throughput. This gives a small fitness bonus to a large number small I/O's. In the throughput phenotype, the fitness simply looks at the number of sectors read or written in during a child's lifetime. This phenotype makes sure data is actually moving, and not just servicing a lot a small requests. The latency phenotype measures the time all requests sit in the queue. This should help combat I/O starvation.

Selection is the process of keeping and eliminating chromosomes in the population based on their relative quality or fitness. In most practices, a roulette wheel approach, rank-based or value-based, is adopted as the selection procedure. In a rank based selection scheme, the population is sorted according to the fitness values. Each chromosome is assigned a sector of the roulette wheel based on its ranked-value and not the actual fitness value. In contrast, a value based selection scheme assigns roulette wheel sectors proportional to the fitness value of the chromosomes. In this paper, natural selection scheme is used. Advantage of natural selection based fitness assignment is it provides uniform scaling across chromosomes in the population and is less sensitive to probability-based selections.

Generally, GAs are composed of two main components that are problem dependent: the encoding problem and the evaluation function. The encoding problem generates an encoding scheme to represent the possible solutions to the optimization problem. In this research, a candidate solution is encoded to represent the sequential, random reads and writes for disk scheduling. The evaluation function measures the quality of a particular solution. Each chromosome is associated with a fitness value, which in this case is the waiting time in the queue. For this research, the smallest value represents the better solution. The fitness of a candidate is calculated here based on its simulated performance.

New chromosomes, called off springs, are formed by (a) merging two chromosomes from the current population together using a crossover operator or by (b) modifying a chromosome using a mutation operator. Crossover, the main genetic operator, generates valid offspring by combining features of two parent chromosomes. Chromosomes are combined together at different crossover rate, which is defined as the ratio of the number of offspring produced in each generation to the population size.

Mutation, a background operator, produces spontaneous random changes in various chromosomes. Mutation serves the critical role of either replacing the chromosomes lost from the population during the selection process or introducing new chromosomes that were not present in the initial population. The mutation rate controls the rate at which new chromosomes are introduced into the population. In this paper, results are based on the implementation of a set of crossover operators, which is mostly used in scheduling problems, and insertion mutation operator that selects a gene randomly and inserts it in a random position.

4. NUMERICAL RESULTS

In the experiments reported in this section, we use Linux kernel 2.6.18.

For each genetic-based scenario, 20 random schedules were generated for the initial population. The poorest 10 schedules were eliminated from the initial population, and the GA population size was kept a constant 10. Natural selection scheme is used that selects the top performers and eliminates the worst performers. The various recombination operators used at a crossover rate 0.9.

4.1. Partially Mapped Crossover

It uses a special repair procedure to resolve possible illegitimacy. Two cut points are selected along the string at random. The sub strings defined

by the two cut points are called mapping sections. Two sub strings are exchanged between parents to produce protochildren. The mapping relationship between two mapping sections is determined. Offspring is legalized using the mapping relationship [3].

4.2. Order Crossover

It can be viewed as a kind of variation of PMX that uses a different repair procedure.

A sub string is selected from one parent at random. A protochild is produced by copying the sub string into positions corresponding to those in the parent. All the symbols from the second parent, which are already in the sub string, are deleted. The resulting sequence contains the symbols the protochild needs. The symbols are placed into unfixed positions in the protochild from left to right according to the order of the sequence to produce an offspring [3].

4.3. Position-based Crossover

It is essentially a uniform crossover for literal permutation encodings incorporated with a repair procedure. It first generates a random mask and then exchanges relative genes between parents according to the mask. It uses a repair procedure to resolve the illegitimacy. It selects a set of positions from one parent at random. A protochild is produced by copying the symbols on these positions into the corresponding positions in the protochild. The symbols already selected from the second parent are deleted. The resulting sequence contains only the symbols the protochild needs. The symbols are placed into unfixed positions in the protochild from left to right according to the order of the sequence to produce an offspring [3].

4.4. Linear Order Crossover

It tends to transmit the relative positions of genes rather than the absolute positions. It selects sub lists from parents randomly. Sublist2 is removed from parent p1, leaving some holes and then slide the holes to the cross section. Similarly, sublist1 is removed from parent1 to form offspring o1 and sublist2 is inserted into the holes of parent p1 to form the offspring O_2 [3].

Insertion mutation is used with probability 0.1. The stopping criteria is that the current population converged (i.e., all the chromosomes have the same fitness value).

4.5. Linux Kernel

Linux kernel 2.6.18 is used for this research.[4] The proc filesystem,which is a pseudofilesystem rooted at /proc contains user-accessible objects that pertain to the runtime state of the kernel and, by extension, the executing processes that run on top of it. The proc filesystem exists only as a reflection of the in-memory kernel data structures it displays. This is used to port the results to domains outside disk scheduling.

Table 1 Fitness Values for Different Crossover Operators

	No of Population			
Crossover	100	200	300	400
Partially mapped Crossover	63.009	71.093	67.987	61.129
Order crossover	62.267	71.093	86.002	61.129
Position-based crossover	61.129	75.489	71.093	62.980
Linear order crossover	63.980	76.987	75.400	64.491

From the table, it is shown that as number of population is increased, Genetic Algorithms performance is improved.

5. CONCLUSION

In conclusion, preliminary data demonstrates that using GAs for Anticipatory scheduling in Linux scheduling can provide improved performance. But there is a strong argument that it adds extra complexity to the kernel. Future work will be conducted to more completely study the effect of changing parameters of the GA, including crossover and mutation rates as well as the methods used for crossover and mutation. Finally, future studies will be conducted to determine the performance improvement by using Lamarckian parameters.

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MODELING CONSTRUCTION SAFETY AS AN AGENT-BASED EMERGENT PHENOMENON

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ABSTRACT
Traditional research in construction safety focused on accident data analysis, identification of root cause factors and safety climate modeling. These research efforts did not study the dynamic repetitive interaction among multiple root cause factors. Recently safety research focuses on developing accident causation models. These models attempt to explain how the interaction among multiple project factors gets translated into safety incidents. Agent based modeling and simulation (ABMS) is an appropriate technique to develop computational models of accidents causation because of its ability to model human factors and repetitive decentralized interactions. This paper presents a conceptual framework for developing agent based models of construction safety. The key components of the model such as construction crew, management, work environment, material and equipment related quality issues, project/process level complexities, interaction rules and adaptation have been discussed. Further the adaptation of agents in response to the safety culture has been demonstrated using a simple ABMS experiment

KEYWORDS
Construction Safety, Agent Based Modeling and Simulation, Construction Accidents Causation

1. CONSTRUCTION SAFETY

Data published by the Bureau of Labor Statistics shows that there were more than 1000 fatal and 400,000 non fatal incidents in construction industry in the year 2005 [1]. Although the total number of construction related non fatal injuries and illness cases reduced from 529,300 (in year 1994) to 401,100 (in year 2004), it is a concern to note that the construction related fatal incidents increased from 1028 (in year 1994) to 1234 (in year 2004) (Figure 1). Construction related safety incident numbers are significant even in the year 2005 (1243 fatalities and 414,900 non fatal incidents). Assuming that 220 working days in a year, on average, there were 5.65 fatal and 1885 non fatal incidents every day in the year 2005. Most of the construction fatalities and injuries occur due to falls from height or struck by a moving or falling object [2]. Safety incidents occur due to production pressure [3] or inefficiencies in project planning such as lack of training, protective wearing, absence of appropriate mechanical hazard elimination, poor site house keeping practices and lack of quality in construction material/equipment [2, 4]. Previous research in construction safety focused on analysis of safety accidents data [4], identification of root cause factors [4], and safety climate analysis [5, 6]. However, the knowledge

on how the multiple root cause factors such as management, crew, site, equipment, material and project/process level complexities dynamically interact and gets translated into safety incidents has generally not been captured. Recent research works focused on understanding the hierarchy of causal influences [2], map system structure with causation of accidents [7], and to develop accidents causation models [3, 8]. The basic motivation behind these works is to understand the interaction among multiple root cause factors and explain how the interaction among these factors gets translated into safety incidents.

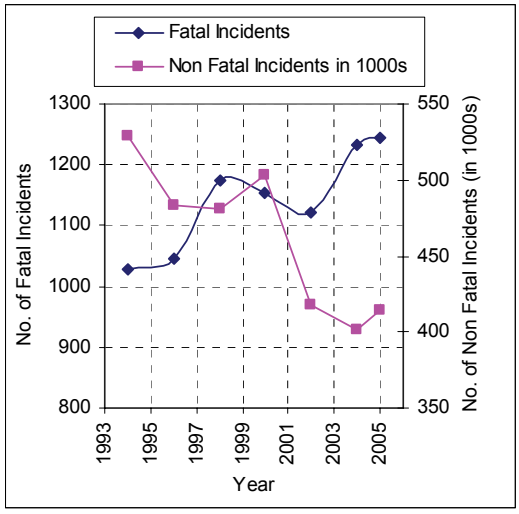


Figure 1 Construction Related Fatal/Non Fatal Incidents (Source: U.S. Bureau of Labor Statistics)

2. AGENT BASED SIMULATION

Agent based models are primarily used to simulate decentralized complex adaptive emergent systems in social, economic and environmental sciences [9]. Agent based model provides a realistic natural representation of the system using object oriented concepts. Some of the key features of agent based simulation models are [10]: i) Agents have diverse set of properties and rules that mimic the real world behavior; ii) Simple rules at the micro level create complex behavior at the macro level; iii) Agent based systems are mostly bottom-up systems, i.e. no top down control; iv) Agents interact and learn from other agents; v) Agents interact with the operating environment; vi) Agents adapt over a period of time; and vii) The characteristics of the operating environment change during interaction with agents.

2.1 Review of Literature: ABMS in Construction

Several attempts have been made to apply agent based modeling and simulation concepts in construction. An agent based approach was presented to dynamically re-schedule the project by all concerned coordinating subcontractors [11]. A multi-agent systems based approach was proposed to improve the efficiencies of construction claim negotiation process among distributed construction team members [12]. The use of agent based models to simulate the construction processes in production home building has been demonstrated [13, 14]. Further the adaptation of construction crew in response to the company safety culture has been demonstrated using an agent based simulation experiment [15]. The state-of-the-art on the applications of multi-agent systems for collaborative construction engineering activities has been reviewed [16]. An agent based proto-type system was developed using ZEUS toolkit to model and simulate the dynamic interactions and the inter-dependencies in collaborative project supply network [17]. A multi-agent based simulation model has been proposed to study the influence of inter-firm relations in construction organizational networks [18]. Further, a computational model has been developed to analyze the human and social behavior in emergency evacuation situations [19].

3. MOTIVATION AND OBJECTIVES

A large body of literature is available in construction safety domain about the root cause factors of accidents. Similarly, statistics on construction accidents such as fatalities, major injuries, minor injuries, near misses, number of lost working days, incident rate are available in literature. However, there is limited research conducted on how the root cause factors interact with each other in a repetitive manner and gets translated into safety incidents. The interaction among these factors happens at multiple levels namely immediate level, shaping level and originating level [2: Fig.2]. A series of safety rule violations that propagate from the originating level to the immediate level may finally result in the

occurrence of a safety incident if they are not identified and treated appropriately [7: Fig.2]. Developing computational models for construction accidents causation can help us understand the interactions among root cause factors and provide possible explanation on how the interaction among these factors gets translated into safety incidents.

This work attempts to investigate how ABMS can be utilized to explain some of the key issues in the construction accidents causation process. The two objectives of this work are: i) develop a conceptual framework that illustrates the key components of an agent based simulation model for a construction safety system; and ii) implement a conceptual ABMS model that demonstrates the some of the key construction safety concepts.

4.0 CONCEPTUAL FRAMEWORK OF AGENT BASED MODEL FOR CONSTRUCTION SAFETY

The key components of an agent based simulation model for construction safety system consist of the following: (i) agents with diversity in agent types, properties and rules; (ii) work environment characteristics – safety risks as a function of location and space availability; (iii) project planning practices and safety policies of the management; (iv) material, equipment characteristics and associated quality issues; (v) project/process level complexities and its impact on interaction among root cause factors; (vi) rules for interaction - agent to agent (coordination), agent to site (hazardous situations), agent to management (production pressure) and agent to material/equipment (quality issues); (vii) adaptation in agent properties and rules; and (viii) changes in the company policies and (ix) changes in the work environment. The dynamic repetitive interaction among multiple root cause factors is shown in Figure 2.

4.1 Agents with Diversity in Agent Types, Properties and Rules

Examples for agents in construction projects include project manager, construction manager, project superintendent, site superintendent, general foreman, equipment operator, skilled labor and unskilled supporting labor. Effective coordination of multiple agents is critical for completion of the task in a timely and safe manner. Each agent has a set of properties based on personal factors and professional job responsibilities. Some of the personal variables that characterize agents include age, personal traits (safety conscious or productivity conscious), attitude, motivation, job satisfaction, fatigue, alcohol use, lack of sleep, disease, and worry or anxiety [4]. Variables related to work environment include knowledge, skill level or competency, duration on site (in months), duration in the industry (in years), duration with employer (in years) and average designated hours per week [2, 4].

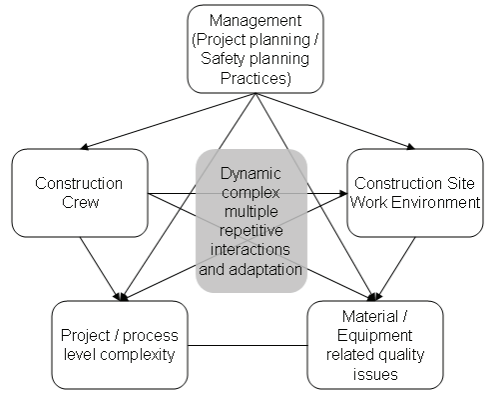


Figure 2 Interaction Among Root-Cause Factors

4.2 Site: Work Environment Characteristics

Construction project sites have diverse set of characteristics. Examples include hazardous conditions inherent in the work (work in high elevation or in deep trenches, work near high voltage power cables or heavy traffic), weather conditions (windy, rain, drizzling, heat stroke, snow), time of work (day or night), site layout and space availability (congested site with limited space or ample space without any restriction), operating conditions (noise, dust or slippery walking surfaces), local or protruding hazards (such as nails, scaffolding components). These factors are influenced by site constraints, work scheduling and site house-keeping practices and they change continuously during the construction process [2]; hence dynamism i.e. constantly changing work place and work activities is an inherent nature of construction sites. The location

of the work place and the availability of workspace influence the safety risks of construction crews.

4.3 Management Factors

Management factors directly control on how the project planning practices and safety policies are implemented in a construction project. The safety climate on a construction site is strongly influenced by management factors. Examples for management factors include safety culture (priority for production or safety), training, provision of PPE, appropriate mechanical hazard elimination, site housekeeping practices, and availability of quality construction materials, equipments, and machine tools. Further, the management factors are responsible for enforcing safe work practices in various project life cycle activities such as design, scheduling, coordination and communication (safety tool box meetings) and task execution.

4.4 Material, Equipment Factors and Associated Quality Issues

At the immediate level [2], the suitability, usability and the condition of the materials and equipment influence the likelihood of construction accidents. Based on the analysis of 100 accidents [2], it was found that accidents happen 27% of the times due to material related factors and 56% of the times due to equipment factors. Material and equipment related factors are influenced by design, specification, supply, availability, and maintenance at the shaping level, and by management (construction education, economic climate and client requirements), supply vendor factors at the originating level [2].

4.5 Project / Process Level Complexities

Certain inherent characteristics of construction projects and construction processes influence the likelihood of accidents. The safety at the project and process level is influenced by shared resources, constraints related to the location of workspace and the limited workspace availability. For example, shared or congested workspace across multiple crews increases the likelihood of one crew being affected by the action of another crew. Similarly shared resources such as cranes between two different activities increase the work pressure on the equipment as well as on the equipment operator. Examples for process level complexity can include working on high elevations, underground infrastructures such as tunnels or deep trenches, and proximity to high voltage power cables, etc. Some of the project related factors include project duration, project delivery methods, schedule status (ahead of schedule, on schedule, or behind the schedule), crew size, etc. The task or process level complexity is also a function of the type of the task. Different types of tasks include setting-up, actual task, clear-up, maintenance and movement or transit.

4.6 Interaction Rules

A number of interactions happen during construction processes depend on the rules of participating agents. These include agent to agent interaction (coordination), agent to site interaction (hazardous situations), agent to equipment/material (quality issues) and management to agent (safety climate and production pressure). Some of the rules for agents include coordination, learning from other agents, ability to influence the performance of other agents, act in response to the company policies and act in response to the characteristics of the work environment. When there exists more production pressure, construction crew increases the pace or speed of their work and tend to be less cautious toward safety rules. On the other hand, when there is a rewarding atmosphere for safe performance, crew pays more attention to safe work practices. Management rules include designing project planning practices and safety policies in response to the project progress at specific time intervals. When the project is behind the schedule, management may exert work pressure on crews. Increased stress and production pressure may lead to non-compliance of safety rules by the crews and eventually this might result in the occurrence of safety incidents. Provision of safety training, regular safety tool box meetings, appropriate mechanical hazard elimination and selection of quality material, equipment and hand tools positively influences safety climate of the construction projects. Often the safety requirements are considered as conflicting goals with the productivity [3]. But when a safety accident occurs at the construction site,

management will tend to pay more attention to safe work practices after that incident.

4.7 Adaptation

Adaptation refers to the change in the properties and the rules of the agents in response to the changes in the company policies, changes in work environment characteristics. For example, a front line manager plays an important role in implementing safe work practices at construction sites. If the front line manager is safety conscious and has good interaction with onsite crews, then the onsite crews adapt toward a highly safe working atmosphere. On the other hand, if the front line manager lacks safety training and have poor interaction with crews, then this may lead the onsite crews to be non compliant toward safe work practices. The characteristics of the work environment change continuously during the construction; for example change in site layout, change in geometric conditions of the site structures etc. Further the management planning and policies adapt over a period of time in response to the project status and the safety based performance of the crew.

4.8 Discussion on the Conceptual Framework

While most of the agent based applications in social science domain are described by only bottom-up processes, its application in construction requires certain changes to existing concepts. This is because the representation of construction processes requires a combination of top-down control (management factors, federal regulations, state/local regulations) and bottom-up control methods (localized interactions, real-time behavioral decisions). Development of agent based models for construction safety domain involves modeling complex multiple repetitive interactions and adaptation among construction crews, management policies, work environment, material/equipment related quality issues and the project & process level complexities. This can be a challenging task given the large number of variables, complexities involved in the interaction as well as in the adaptation. The scope and the level of details of the agent based simulation model can be decided based on the type of safety related questions that needs to be answered.

5.0 SIMULATION EXPERIMENT

This section presents the results of a simple conceptual agent based simulation experiment that demonstrates the adaptation of construction agents in response to the safety culture of the construction firm. This experiment is a confirmation and conceptual extension of the work reported by Walsh and Sawhney [15]. The agent based simulation tool "NetLogo" was used for this experiment. NetLogo was developed by the Center for Connected Learning and Computer based Modeling at Northwestern University (http://ccl.northwestern.edu /netlogo/).

5.1 Simulation Model Description

Agents: There are 50 agents in the model. Agents keep moving from pick location to place location to transport materials in a simulated construction site environment. Agents have the following properties: care-taken and speed. Care-taken refers to the safety consciousness of the agents. This means how cautious the agents are while they make each step in the site. Care-taken value is a function of many variables such as training, familiarity of the agent with the crew member and with the supervisors, number of supervisors in the site, etc. In this model, care-taken varies uniformly from 0 to 200. Speed refers to the number of steps that an agent can move forward in each time step of the simulation clock. It is assumed that speed is inversely proportional to care-taken (for example, speed is 1 if care-taken is 200; speed is 5 if care taken is less than or equal to 100).

Site: The site is represented as a two dimensional grid of size 50 by 30 cells. Each cell or patch is associated with a danger value. The danger value is function of site house keeping, site complexity and site conditions based on environmental factors. In this model, it is assumed that danger value varies uniformly from 0 to 200 for each cell.

Agent rules: (1) The number steps that an agent moves toward pick or place location is equal to the speed of the agent. Per simulation clock time step, an agent with speed 1 makes one step whereas an agent with speed 5 makes 5 steps. (2) After completing each step, the possibility of safety incident is checked. If the care taken value of the agent is greater than the danger value of the

current patch or cell, then there will be no incident. On the other hand, if the care taken is less than the danger value, there is p% chance for the occurrence of safety incidents. The value of the variable 'p' can be controlled by the user (in this model p is assumed as 2%). (3) Each agent's performance is measured using two variables: 'safety-inc' refers to the number of safety incidents and 'prod-cycles' refers to the number of production cycles completed by the agent. (4) The score for each agent is computed using the following equation: Score = production cycles X production weight – number of safety incidents X safety weight (production weight refers to the priority given by the management toward production; similarly safety weight refers to the priority given by the management toward safety; these weights vary from 0 to 100). (5) After completing 1000 simulation clock steps, it is assumed that one generation is completed. After this the generation index is incremented by one and the simulation is continued for a specific number of generations. (6) After the completion of each generation, agents in the simulation model adapt. The agents are ranked based on score value. The values of speed and care-taken variables of bottom six agents (in terms of low score) are replaced by the average care-taken and average speed of top 12 agents.

5.2 Simulation Results

The simulation model was initially developed in NetLogo. NetLogo provides a combination of visual animation, dynamic plots, trace and Excel based analysis report using Behavior Space. However, to minimize the run time and to produce customized output that is very specific to the modeler in each iteration (when visual animation is not needed), agent based model can be implemented using programming languages like C++. Developing agent based models using C++ supports modeling complex logic using powerful data structures. To accomplish this, the same model was re-implemented in C++. In this work, a combination of NetLogo and C++ based models were used for analyzing different scenarios.

Two types of experiments were conducted using the developed model. The first experiment studies the changes in the agent population characteristics in response to the safety culture in the firm. The safety culture influenced by the management is represented using two variables namely safety weight and production weight. The following test cases were tested: (i) safety weight: 100, production weight 0; (ii) safety weight: 100, production weight 50; (iii) safety weight: 50, production weight 100; (iv) safety weight: 10, production weight 100; and (v) safety weight: 0, production weight 100. The average care-taken of the agent population was plotted with respect to generations in each case. Figure 3 shows the summary of results of 5 test cases for the first experiment.

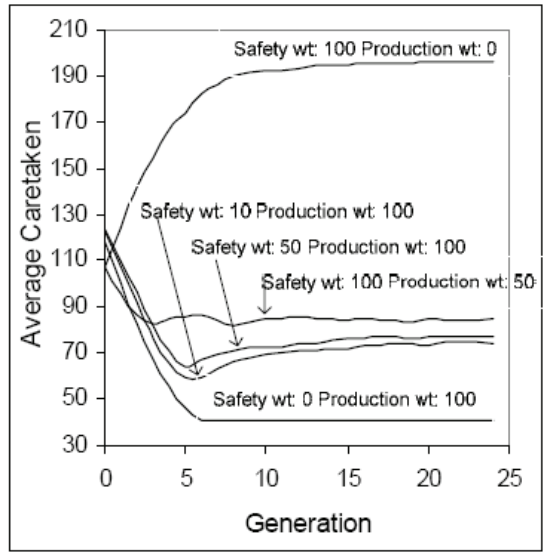


Figure 3 Plot of Average Care-taken

It can be noted from Figure 3 that the variation in the average care-taken of the agent population across generations is directly proportional to the safety weight and it is inversely proportional to the production weight. When the safety weight is 100 (priority is given for safety), agents adapt toward higher safety consciousness or care-taken. On the other hand, when the safety weight is zero (priority is given for production), agent population adapt toward least safety consciousness or care-taken.

The second experiment is an extension of the work reported by Walsh and Sawhney [15]. This focuses on modeling the variability in the adaptation of agent population for a given safety culture (safety and production weights). In real scenarios,

variability in agent's adaptation assumes significance. Even for a given safety culture, construction crew adapts in different ways depends on the factors related to personal (training, learning and motivation), site, management, material/equipment and project/process complexity. Three types of adaptation namely 'low', 'medium' and 'high' were defined and tested in this experiment. Adaptation rate defines the rate of learning and increase in the agent's safety consciousness i.e. care-taken in each generation in response to the safety weight. In every generation, the care-taken value of bottom six agents were incremented by 20%, 40% and 60% for the three types of adaptation rates 'low', 'medium', and 'high' respectively. Figure 4 shows the plot of average care-taken of agent's population for three types of adaptation (safety weight: 100 and production weight: 0 for all 3 cases). When the adaptation rate is high, the average care-taken value of the agent population reaches maximum in 17 generations. On the other hand, when the adaptation rate is medium or low, the agent population needs more number of generations to reach high level of safety consciousness.

6.0 CONCLUSIONS

ABMS can be used to develop computational models of construction accidents causation since it supports modeling human behavioral factors and local repetitive interactions among multiple agents and entities at construction site. The resultant model may help us to understand the dynamic interaction among multiple root cause factors and provide possible explanation on how the interaction among root cause factors gets translated into safety incidents. This paper presented a conceptual framework for developing agent based models of construction safety. The key components of agent based model such as construction crew, management, work environment, material and equipment related quality issues, project/process level complexities, interaction rules and adaptation have been discussed. The adaptations of agents in response to the safety culture and the variability in the adaptation have been demonstrated using a simple NetLogo simulation experiment. Development of a realistic agent based model requires thorough understanding of construction operations and collection of safety data from construction sites for the various factors discussed in the conceptual framework. Given the fact that the development of construction accident causation models is being actively pursued by safety researchers recently, agent based modeling and simulation technique is one of the suitable alternatives to develop computational models of construction accidents causation.

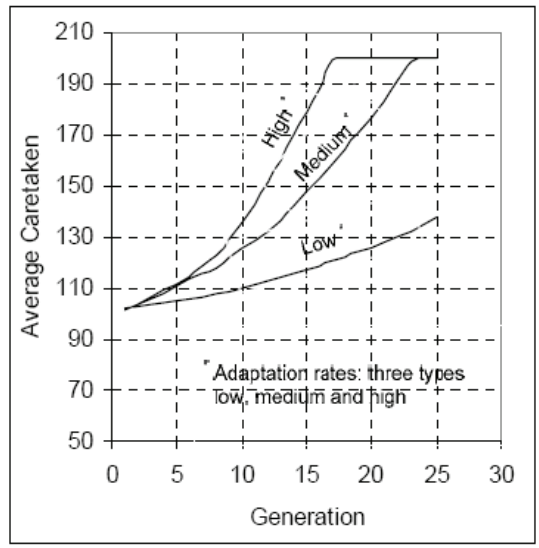


Figure 4 Plot of Average Care-taken for Three Adaptation Types (Safety Wt: 100, Prod. Wt: 0)

7.0 ACKNOWLEDGMENTS

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A CAD-BASED SITE LAYOUT FOR IRREGULAR FACILITIES USING ACO

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ABSTRACT

This paper introduces a novel approach to enhance the general practice of layout planning of construction sites for producing the efficient utilization. In this work, a solution to the problem is attempted for unequal and irregular temporary facility using robust search and optimization capabilities of Ant Colony Optimization (ACO) algorithm, inspired by the foraging behaviour of real ants. The problem is solved in four stages, namely (1) discretising construction space and formation of representative matrix of site and temporary facilities, (2) identifying all practical constraints in this optimization problem, (3) dividing the construction project in various time interval and identifying the temporary facility for the corresponding time interval, and (4) implementing ACO to get the optimum position and orientation of temporary facilities

KEYWORDS

Site Layout Planning (SLP), Irregular Temporary Facility, Ant Colony Optimization (ACO)

1. INTRODUCTION

Spatial planning of all activities in construction project is a fundamental necessity for successful completion of the project. Construction site layout involves coordinating the use of limited site space to accommodate temporary facilities needed to support construction operation such as fabrication shops, trailers, materials, or equipments so that they can function efficiently on site. The layout problem is generally defined as the problem of (1) identifying the shape and size of the facilities to be laid out, (2) identifying constraints between facilities, and (3) determining the relative positions of these facilities within the boundaries of the available space on the site so that it satisfies the constraints between them and allow them to function efficiently.

Despite its importance, site planning is often neglected, and the attitude of engineers has been that it will be done as the project progresses. Conventionally, the site layout is planned purely based on past experience of construction manager. It could not be possible to handle efficiently and judiciously a large number of facilities, factors and complexity involved in the site plan based on knowledge gained by experience only. This lack of proper site layout planning results in loss of productivity in the form of increased transportation cost, reduced safety, increased frequency of trips, and increased relocation costs. An efficient planned site could result in (i) reduction in project cost, (ii) decrease time and effort spent on material handling, (iii) improvement in quality of work (iv) increase productivity, (v) improvement in safety of operation of the project, and (vi) decrease of

completion time of project. One of the main ways in which a site layout can achieve the objective is by the minimization of travel time and removal of unnecessary movement of resources and handling material.

In present work a novel approach to enhance the general practice of site layout planning for producing efficient layout is presented using Ant Colony Optimisation (ACO).

2. LITERATURE REVIEW

A number of studies were conducted in order to improve site layout planning in construction projects. These studies adopted a wide range of methodologies and development tools including neural networks, simulation, knowledge-based systems, and genetic algorithms. Tommelein et. al. [1] used artificial intelligence techniques to solve site plan layout. Yeh [2] used annealed neural networks to arrange a set of predetermined facilities on a set of predetermined locations on construction sites. Several expert systems and knowledge-based systems were also developed to integrate domain knowledge of experts and assist in facility layout planning tasks [3, 4]. Other studies proposed heuristic algorithms including the use of the early commitment criterion to design site layouts [5]. Tam et. al. [6] investigated and analyzed the relationship between the key storage areas and the tower crane and to develop a GA model to optimize the facilities, taking into account the complexity of the relationship between these facilities. A single-tower-crane optimization model is applied with assumptions. The function is total cost as a sum of the product of Hook Travel Time [7], quantity of material flow and cost of material flow from Source to Destination per unit quantity and unit time. Genetic algorithms were used in several studies to optimize the layouts of construction sites [6, 8-11]. These genetic algorithms have shown improvements in the search process for near optimal solutions, especially in this type of problem that is characterized by a large search space.

Elbeltagi et. al. [12] recognized site layout as a dynamic problem at various schedule to accommodate operational need considering both safety and productivity. As construction evolves, however, the site layout may need to be dynamically reorganized at various schedule intervals to accommodate operational needs. As opposed to considering only productivity issues during site planning, this paper presents a layout planning approach that considers both safety and productivity. First, safety issues on construction sites are discussed and the factors that contribute to unsafe sites are outlined. A procedure for optimum layout of temporary facilities is then developed in integration with a scheduling tool. This paper presents an effort to provide a practical model for dynamic site layout planning in construction that when implemented will assist in maintaining safety and productivity on construction sites.

Chau [13] solved the large size problem using GA as a two-stage dynamic mode developed to assist construction planners to formulate optimal strategy for establishing potential intermediate transfer centers for site level facilities. Zouein and Tommelein [5] also solved problem as dynamic layout planning using a Hybrid Incremental Solution Method.

Fuzzy based [14] site plan layout problem is solved for multi-objective evaluation of transport cost, safety, and visibility. The paper investigates the use of fuzzy based multi-objective optimization approach in making a more infirmed strategic decisions regarding the movement path of people and vehicles on construction sites, and detailed decisions regarding travel distance and operational paths on workplaces, enabling site planners to examine path scenarios that are subjected to high degree of uncertainty and subjectivity.

An attempt has been made by investigators [15, 16] to integrate the computer aided design and site layout planning. Osman et. al. [16] employed GA for site layout optimization integrated with CAD drawing. Sadeghpour et. al. [15] employed object based model for integration. Varghese and O'Connor [17] has integrated expert system, geographic information system and CAD for route planning on construction site.

In the present work, a CAD based site optimization has been carried out considering Ant colony optimization. The present work is a contribution

in the field of automation for design-construction operation.

3. SITE LAYOUT OPTIMIZATION

3.1 Site Layout Problem

To arrange a set of predetermined facilities into appropriate locations, while satisfying a set of layout constraints, is a difficult problem as there are many possible alternatives. Site layout planning can generally be classified according to two main aspects:

1. Method of facility assignment and
2. Layout planning technique.

With regard to the method of facility assignment, or in other words, the manner in which temporary facilities are assigned on site, two distinct methods are commonly encountered. The two methods are

1. Facility to location assignment and
2. Facility to site assignment.

With regard to layout planning, two distinct techniques are commonly encountered. The two techniques are called

1. Mathematical planning
2. Knowledge based planning

In this work, mathematical planning based approach has been used. We shall write objective function for site optimization.

3.2 The Objective Function

Effective placement of temporary facilities within the site improves the movement of resources, or the interactions among facilities. Such interactions are referred to as closeness relationships (weights) among the facilities and represent the desirability of having the facilities close or apart from each other [9]. Traditionally, closeness relationships have represented aspects that relate only to productivity and could be set as the actual amount material moved between facilities or the actual transportation cost. In the literature, six closeness relationships are usually set in advance, and the user can give desired weight values associated with category as shown in Table 1.

Although example presented considers only static site optimization, dynamic site layout has been presented for objective function.

Depending on the type and extent of the construction problem, a period can be given in terms of months, quarters, year etc. The major question involved in the site layout is what should be the layout in entire period of construction. The objective of dynamic site layout is what should be the layout in each period, or to what extent, if any changes in the layout should be made.

Table 1 (Osman et al. 2003) [4]

Desired Relationship between facilities	Proximity weight
Absolutely necessary (A)	81
Especially Important (E)	37
Important (I)	9
Ordinary closeness(O)	3
Unimportant (U)	1
Undesirable (X)	0

The costs associated with the dynamic site layout are those pertaining to the flow of the personnel and material and those involved with rearrangement of the layouts. The material flow costs are a product of proximity weight and distance. Cost of installation of facility at different location of site may be different. Rearranging of facility will result in some shifting cost considering this shifting the installation cost at same position in different time span may be different. The rearrangement cost may be obtained as cost, depending on the facilities involved and the distance between the various locations. Cost associated with site layout are:

(1) Flow cost of the personnel and material define as:-

$$f1 = \sum_{i=1}^{m} \left(\sum_{j=1}^{n} \sum_{k=1}^{n+p} f_{ijk}\, d_{X_{ij} X_{ik}} \right) \quad \text{.....(1)}$$

Where i is index for period; m is total number of period; *j,k* is index for facility, *n* is total number of temporary facility, *p* is total number of permanent facility, f_{ijk} is cost per unit length for material flow, x_{ij} is location allotted for facility k in period i,

$d_{x_{ij}x_{ik}}$ is distance between facility j and k in period i. f_{ijk} value representing either the actual transportation cost per unit distance between facilities i and j (taking into consideration the number of trips made) or a relative proximity weight that reflects the required closeness between facilities i and j. Using actual transportation costs to represent, the term f_{ijk} has the clear objective of minimizing the total transportation costs between site facilities. The objective is not as apparent when using the relative proximity weight representation. However, obtaining accurate values for the actual inter-facility transportation costs can become quite difficult, especially during project planning stages. This limitation promotes the use of proximity weights instead as they are generally much easier for the site planner to provide.

(2) The cost of rearrangement of the facilities defined as:-

$$f2 = \sum_{i=0}^{m+1}\left(\sum_{j=1}^{n}\left(\frac{\left|X_{i+1,j} - X_{i,j}\right|}{\left|X_{i+1,j} - X_{i,j}\right| + \varepsilon}\right)b_{j,X_{i,j}} + c_{i,j}\right) \quad ..(2)$$

Where i=0 and i=m+1 are for calculating the installation cost in the first period and remove cost in last period, when construction is over or there is no need of temporary facility at construction site.

Considering both total cost interaction of facility as well as installation and removal cost of facility, the objective function will be:-

$$f = \min(f_1 + f_2) \qquad \ldots\ldots (3)$$

Dynamic site layout problem will be converted to static layout problem if value of $m = 1$. For this value, total no of time span for which temporary facility to be locate at construction site will be one so intermediate shifting or relocating of facility will happen but it will include initial allocation and final removal cost.

Input to the model will consist of three types of matrices named as F, B, C. Here F is an n×n matrix which indicates the flow cost between facilities in m period, B is an n×n matrix which represent installation cost and C is also an n×n matrix which defines the removal cost.

4. PROBLEM IMPLEMENTATION

Case studies have been done to check the performance of the model in different stages of development. In the initial stage, the model was applied to a hypothetical problem with rectangular temporary facility and rectangular irregular facilities. The details of the implementation for integrating CAD with ACO based site optimization are shown in the flow chart in Figure 1. Detailed implementation is given elsewhere in the project report [18, 19].

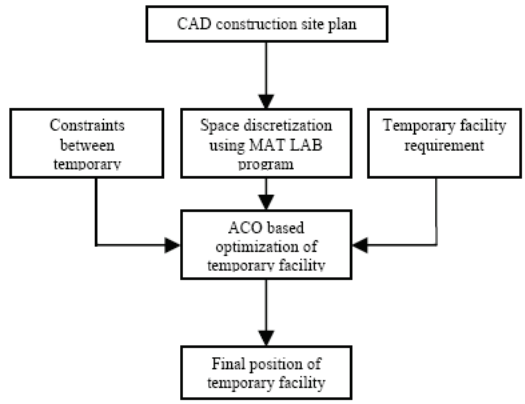


Figure 1 Flow Chart for Implementation

The performance of the model is compared with the result obtained by GA. It was modified for irregular temporary facility in the same problem.

4.1 Application to the Simplified Hypothetical Problem

The details of the problem are as follows. Boundary is 500m x 400m; No. of permanent facilities is 5; No. of temporary facilities is 5 (Rectangular).

Table 2 Details of Facilities

Permanent Facilities		Temporary Facilities	
Facility No.	Access Point Location (x,y)	Facility No.	(Lx, Ly)
1	128, 294	1	(50, 50)
2	348, 260	2	(40, 30)
3	217, 192	3	(30, 30)
4	81, 97	4	(20, 20)
5	350, 68	5	(30, 50)

Where (Lx, Ly) = (Length along x-axis, Length along y-axis) and (x, y) = (x-coordinate, y-coordinate). Affinity matrix is considered based on the six-value scale presented in Table 3.

The result of site layout using GA and ACO is shown in Table 4 for rectangular shape of temporary facilities.

Table 3 Affinity Matrix

Facilities	T1	T2	T3	T4	T5	P1	P2	P3	P4	P5
T1	X	E	I	O	X	X	O	O	A	X
T2	E	X	X	U	X	E	X	O	E	E
T3	I	X	X	X	X	E	A	O	E	I
T4	O	U	X	X	X	A	O	O	X	X
T5	X	X	X	X	X	A	A	X	X	X

Table 4 Site Layout for Rectangular Shape

Temporary facility no.	Position of centroid	
	X,Y (GA)	X,Y (ACO)
1	91,55	92,56
2	110,105	110,106
3	286,229	286,228
4	129,283	129,283
5	215,251	210,252
Objective function	**69223.15**	**68844.50**

Table 5 Temporary Facility

Temporary facility no	Maximum dimension		Shape
	X	Y	
1	50	50	Triangular
2	40	30	Triangular
3	30	30	Triangular
4	20	20	Circular
5	30	50	Elliptical

4.2 Modified Hypothetical Problem (Irregular Shape or TF)

The problem considered is same as the previous problem with irregular boundary of temporary facility. All Permanent facility have the same position and shape as mentioned in previous problem but shape and size of temporary facility is changed from regular to irregular. Temporary facilities changed to different shape and size having maximum x and y length same as previous problem. The result of the ACO is shown in Table 6. Figure 2 shows the final result of the integrated CAD and site optimisation program for irregular temporary facilities.

Table 6 Result of Actual vs. Rectangular Shape

Temporary facility no.	Position(X,Y) of Centroid (using ACO)	
	Assuming rectangular	Taking Actual shape
1	92,56	59,71
2	110,106	108,103
3	286,228	300,233
4	129,283	128,283
5	210,252	220,250
Objective function	**68844.50**	**66349.15**

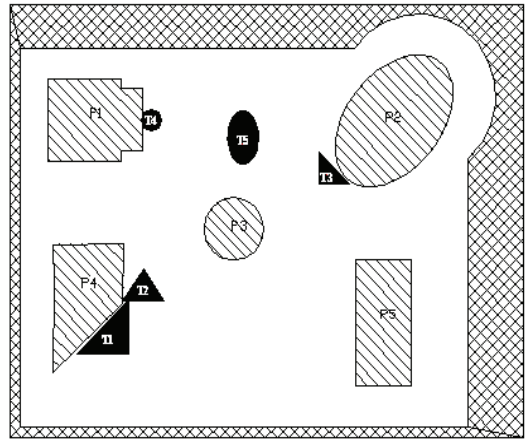


Figure 2 Site Layout of Irregular Temporary Facility

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ECONOMIC EVALUATION MODEL FOR POST-EARTHQUAKE REPAIR/REHABILITATION OF BRIDGE

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ABSTRACT

Taiwan's location in a zone of strong seismic activity means that earthquakes regularly threaten human life and transportation facilities. The importance of bridges in Taiwan's transportation grid makes the destruction or damage of such during earthquakes impact significantly on people's livelihood. However, within the grid, the importances of individual bridges differ from one another in terms of their importance/impact on society. Therefore, a key element in reducing overall economic costs is determining in a quick and efficient manner which bridges deserve priority consideration for immediate repair/rehabilitation following a destructive natural incident. Thus, this research establishes an economic evaluation model for post-earthquake bridge repair/rehabilitation to enhance the effectiveness and efficiency of decision making. Engineering and additional travel costs are then assessed to evaluate the lowest cost and shortest time within all repair/rehabilitation schemes in order to identify and define the optimal emergency plan.

KEYWORDS

Bridge, Earthquake, Repair, Rehabilitation, Economic Evaluation

1. INTRODUCTION

Taiwan, in a zone of significant seismic activity, is notable for its mountainous terrain and numerous river systems. Road system construction requires the regular use of bridges to span natural barriers. Bridges, therefore, represent a vital link in Taiwan's transportation grid, necessary to move both the daily necessities of life and the imports and exports that remain the lifeblood of Taiwan's economy. Damage to bridges in a severe earthquake will inevitably impact communications, delay or cut the transit of urgent aid and materials, and seriously impede the decision making process. Appropriate bridge repair/rehabilitation activities should be carried out as soon as possible to maintain a minimum level of performance [1]. While there has been a considerable increase recently in research on the repair and rehabilitation of damaged bridges [2], authors have not effectively considered in their research the issue of economic needs and benefits [3, 4, 5]. Consider the problem posed by a damaged bridge that links two areas with low population densities. Bridge managers face high premiums in maintaining bridge services that demand high costs and provide low benefits. Deciding which bridges deserve immediate repair / rehabilitation and what level of repair / rehabilitation is justified by current budget constraints represent a complex dilemma for bridge managers. An effective bridge repair strategy, therefore, is an optimization problem that must combine a selection of bridges in most need of repair / rehabilitation with different repair / rehabilitation levels in order to maximize the total benefit delivered.

Based on the above, this research offers an analysis model to promote the effectiveness and efficiency of repair/rehabilitation decision making in order to develop feasible repair/rehabilitation schemes using an emergency repair estimation

model, and then constructs a travel cost estimation model, using ArcGIS to find the shortest path and TransCAD to analyze traffic assignments. Engineering and additional travel costs are then assessed in the Economic Evaluation Model to evaluate the lowest cost and shortest time within all repair/rehabilitation schemes in order to identify and define the optimal emergency plan.

2. CATEGORIZATION OF POST-EARTHQUAKE BRIDGE REPAIR/REHABILITATION TECHNIQUES

This research focuses on the reinforced concrete (RC) bridges, various bridge elements were selected according to bridge structures. The categorization of bridge structures and elements is presented in Figure 1. The bridge structures and elements code is shown in Table 1. Different researchers have suggested different maintenance activity classifications and definitions. This research subdivides maintenance into post-earthquake repair and rehabilitation as defined by Harper [6] and Liu et al. [7] and described as follows (see Figure 2.):

(1) Repair activities are those that restore normal surface conditions and extend the useable life of bridges (e.g., patching and sealing).

(2) Rehabilitation activities are those that restore damaged structures to "original" condition (e.g., attaching additional girders or plates).

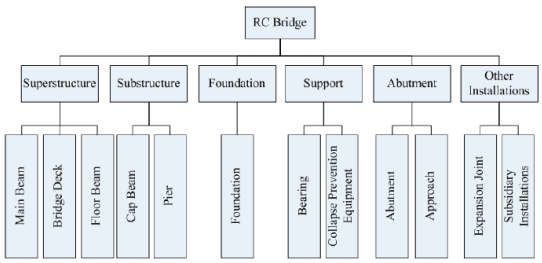


Figure 1 Categorization of Bridge Structures and Elements

3. ESTABLISHING POST-EARTHQUAKE DISASTER EMERGENCY RESPONSE MECHANISMS

The national-level Disaster Prevention and Rescue Committee classifies disaster prevention and rescue measures into three distinct categories. These include disaster prevention, disaster contingency response and disaster restoration and rehabilitation. This research, which established a bridge earthquake disaster response procedure in accordance with the "Basic Plan of Disaster Prevention and Rescue in Taiwan", addresses needs in three categories as follows: "disaster emergency response", "emergency restoration" and "planned rehabilitation and reconstruction".

Table 1 Bridge structures and elements code

Bridge Structure	Structure Code	Bridge Element	Element Code
Superstructure	Sup.	Main Beam; Bridge Deck; Floor Beam	Sup.1; Sup.2; Sup.3
Substructure	Sub.	Cap Beam; Pier	Sub.1; Sub.2
Foundation	F.	Foundation	F.1
Support	S.	Bearing; Collapse-Preventing Equipment	S.1; S.2
Abutment	A.	Abutment; Approach	A.1; A.2
Other Installations	O	Expansion Joint; Subsidiary Installations	O.1; O.2

Checkpoints used in the investigation questionnaire are simple and clear, and therefore, correspond directly to a bridge's overall damage level, which this research categorized into four levels, as follows:

(1) Level A: Abnormal conditions such as serious tilt, sag, bridge deck / support collapse and damage to subsidiary installations which cause a bridge to become impassable. Moreover, damage continues to occur, with further secondary destruction occurring that further restricts passage.

(2) Level B: Abnormal conditions such as tilt, sag, displacement, height differentiation, and support damage that negatively impacts upon bridge safety require that restrictions be imposed upon passage type.

(3) Level C: While abnormal conditions are present, normal passage is unaffected.

(4) OK: No abnormal conditions are present and a bridge is safe to pass.

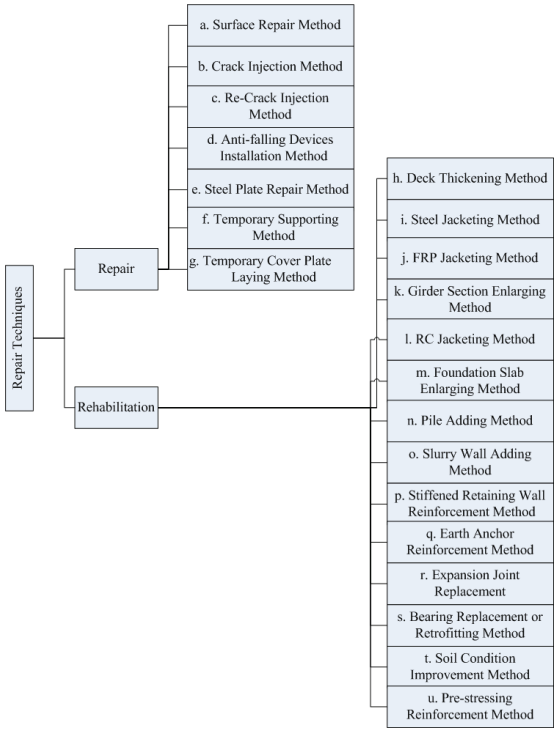


Figure 2 Categorization Framework of Post-Earthquake Bridge Repair Technique

Based on different levels of bridge safety, repair/rehabilitation techniques can then be applied to different emergency procedures.

Finally, research integrates all information to create a relationship between emergency procedures and repair/rehabilitation techniques. This relationship is illustrated in Table 2. Bridge managers can identify suitable repair/rehabilitation activities at different emergency levels by referencing this table.

4. ESTABLISHING AN ECONOMIC EVALUATION MODEL FOR POST-EARTHQUAKE BRIDGE REPAIR/REHABILITATION

Determining which bridges that have been destroyed or damaged require immediate repair/rehabilitation and targeting the proper repair/rehabilitation resources to each bridge represent important tasks for bridge managers. The additional travel costs incurred by road users required to take alternate routes is also a factor that bridge managers should consider when selecting repair/rehabilitation plans. In light of the above, the Economic Evaluation Model for Post-Earthquake Bridge Repair/Rehabilitation was developed to assist bridge managers to evaluate relevant feasible strategies. As shown in Figure 3, the Economic Evaluation Model framework consists of three main parts.

Table 2 Suitable Repair/Rehabilitation in Different Level of Emergency Evaluation

element	Emergency Restoration		
	Level of Emergency Evaluation	First Priority Technique	Further Technique
Sup1	A	a b e	-
	B	f	b i
	C	f	b i

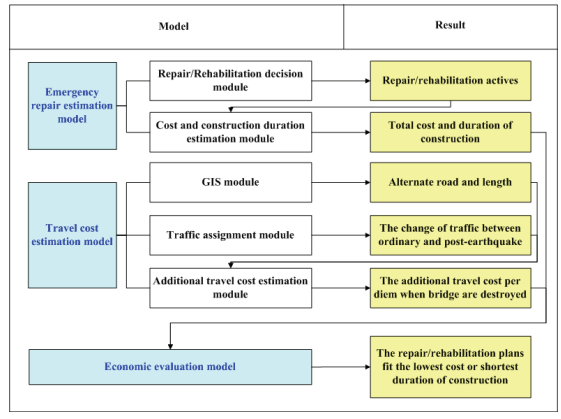


Figure 3 Model Architecture

(1) Emergency repair estimation model: This model derives feasible repair/rehabilitation schemes using a repair/rehabilitation decision module and derives rough cost and construction duration times using a cost and construction duration estimation module.
(2) Travel cost estimation model: This model identifies the shortest path using a GIS module and analyzes traffic information with a traffic assignment module. Both help estimate the additional travel costs attributable to use of an alternate route.

(3) Economic evaluation model: This model integrates the result from the emergency repair and travel cost estimation models. Engineering and travel costs are considered within all kinds of repair/rehabilitation schemes in order to identify the most appropriate emergency plan and maximize total benefit.

4.1 Emergency Repair Estimation Model

4.1.1. Repair/Rehabilitation decision module

This research divides emergency repair into first and second priority categories. Preliminary evaluation results suggest that repair/rehabilitation techniques differ for different evaluation levels. Some pictures taken of the aftermath of the Chichi, Taiwan earthquake (September 21, 1999) help users better appreciate the elements relevant in assigning evaluation levels. The evaluation level will guide the application of specific techniques to different structures and bridge components.

4.1.2. Cost and Construction Duration Estimation Module

Research integrated all repair/rehabilitation information into a form. Users can follow this module to calculate rough costs and construction duration.

4.2 Travel Cost Estimation Model

4.2.1. GIS module

This research applies ArcGIS, developed using ESRI, to build a GIS module to identify the most appropriate alternate route through which to reroute normal traffic flows. A route analysis can be employed in alternate route identification in cases where a bridge is rendered impassable to traffic. The length of the alternate route can then be calculated.

4.2.2. Traffic assignment module

TransCAD is a geographic information system (GIS) designed specifically for transportation professionals to store, display, manage, and analyze transportation data. TransCAD combines GIS and transportation modeling capabilities on a single integrated platform [8]. This research employs TransCAD to perform traffic assignment tasks. Wardrop introduced the User-Optimized Assignment Principle theory into traffic assignment [8], and this study follows Wardrop in using Origin-Destination (O-D) matrix and User Equilibrium to measure traffic flows between the point of traffic interdiction and the nearest point where normal traffic flows without obstruction. The average daily traffic (ADT) value of every route can be calculated using a TransCAD traffic assignment function.

4.2.3. Additional travel cost estimation module

This module reconfigures user cost formulas (Ehlen, Mark A., 1997 [9]) to calculate additional travel costs prior to an earthquake event that disrupts traffic. Maintenance and repair of an existing bridge and the attendant rerouting of traffic can lengthen drivers' commute time and increase vehicle operational costs. Roadway accidents also tend to increase when alternate routes are designated.

Such costs of traffic delays, idle capital, and accidents can be computed using simple formulas based on traffic statistics from Taiwan's Ministry of Transportation and Communications (MOTC). The three types of user costs are typically computed include: 1) Driver delay costs: the personal cost to drivers of delays due to taking alternate routes; 2) Vehicle operating costs: additional costs of vehicle maintenance and depreciation due to taking alternate routes; and 3) Accident costs: costs attributable to vehicle damage and human injury due to taking alternate routes.

Equation (1) can be used to compute user costs attributable to traffic delays due to the enforced use of alternate routes.

$$\text{Driver delay cost}=\left(\frac{La}{Sa}-\frac{Ln}{Sn}\right)\times ADT\times w \quad (1)$$

Where

La: Length of alternate route (Km)

Ln: Length of affected roadway (Km)

Sa: Traffic speed on alternate route during bridge work activity (Km/hr)

Sn: Normal traffic speed on affected roadway (Km/hr)

ADT: Average daily traffic over alternate route, measured in number of cars per day

w: Hourly time value of drivers. The hourly w is typically a weighted average of commercial vehicle driver's and personal automobile driver's time.

Vehicle operating costs can be calculated using equation (2).

$$\text{Vehicle operating costs}=\left(\frac{La}{Sa}-\frac{Ln}{Sn}\right)\times ADT\times r \quad (2)$$

Where

r: Weighted-average vehicle cost, measured in US dollars per day

Accident costs can be calculated using equation (3).

$$\text{Accident costs}=\Delta L\times ADT\times An\times Ca \quad (3)$$

Where

ΔL: $La-Ln$ (KM)

An: Accident rate per vehicle-kilometer

Ca: Cost per accident

Travel cost is equal to the sum of driver delay, vehicle operating and accident costs.

Travel cost (TC) = Driver delay cost + Vehicle operating costs + Accident costs (4)

4.3 Economic Evaluation Model

This model considers bridge repair/rehabilitation costs and duration as well as the additional costs incurred when traffic is redirected through alternate routes. Findings can help bridge manager identify repair plans that maximize benefit. Procedures followed to develop this model are illustrated below:

Step 1: Obtain cost and construction duration estimation module results

Cost and construction duration estimation module results show that cost and duration factors should receive priority consideration, followed by other factors, based on the following equations:

$$MC_{ij}=FMC_{ij}+PMC_{ij} \quad (5)$$

$$MD_{ij}=FD_{ij}+PD_{ij} \quad (6)$$

Where

MC_{ij}: the j-th cost of Element i technique

MD_{ij}: the j-th duration of Element i technique

FMC_{ij}: the j-th cost of Element i first priority technique

PMC_{ij}: the j-th cost of additional Element i technique

FD_{ij}: the j-th duration of Element i first priority technique

PD_{ij}: the j-th duration of additional Element i technique

Step 2: Obtain travel cost estimation module results

Because the travel cost variable is dependent upon construction duration, the maximum value employed to equation (7) to calculate the additional travel cost (TTC) is as follows:

$$TTC_i=MDM_i\times TC \quad (7)$$

Where

TTC_i: additional travel cost (US dollars).

MDM_i: the i-th maximum duration of MD_{ij} (days).

TC: travel cost (US dollars/day)

Step 3: Calculate total cost

Total cost is equal to the sum of the two costs "additional travel" and "construction".

$$RC_j=\sum_{i=1}^{n}(MC_{ij})+TTC_i \quad (8)$$

Where

RC_j: total cost (including the j-th repair/rehabilitation cost) (US dollars).

n: number of elements

Step 4: Economic evaluation of repair/rehabilitation plan

Step 4 calculates the minimum cost and duration of the repair/rehabilitation plan. Bridge managers may select which of the following two equations they wish to use.

$$RCM=\min[RC_j] \quad (9)$$

$$MDM=\min[MDM_i] \quad (10)$$

Where

RCM: minimum cost of repair/rehabilitation plan (US dollars).

MDM: minimum duration of repair/rehabilitation plan (days).

5. THE ECONOMIC EVALUATION MODEL IN PRACTICE – KEELUNG CITY OVERPASS

A case study was conducted in Keelung City, Taiwan employing the economic evaluation model developed in this study. An overpass in a downtown district of that city had been severely damaged in an earthquake and bridge managers were faced with a decision on whether and how to proceed with repair/rehabilitation work in a way that would maximize overall benefit.

Engineers, following procedures and mechanism for post-earthquake bridge emergency response, collected relevant earthquake data and set up public notices regarding bridge damage. The emergency questionnaire indicated damage at Level A, necessitating closure of the bridge to traffic. As part of emergency restoration, photos of similar bridge damage taken in Chichi after the September 21, 1999 earthquake and standard typical damaged drawings were provided to help provide engineers with a larger perspective for their evaluation level (see Figure 4)



Figure 4 Photos of Historical Damaged Cases

In order to decrease user error, form validations and calculations were performed automatically with JavaScript. Level A was designated due to the presence of crevices in beam. Evaluated construction cost and duration are shown in Figure 5.

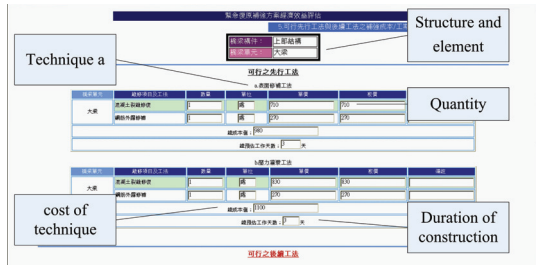


Figure 5 Cost and Duration of Repair/Rehabilitation Evaluation

In the GIS module, the bridge is represented by cross signs and the alternate route and length planned by ArcGIS. Keelung City topography and urban levels were collected and alternate route plans were readied. TransCAD was used to calculate traffic flow in the traffic assignment module. The Keelung City O-D matrix was extrapolated from MOTC data. Traffic assignment equations were bundled in TransCAD.

Total costs, estimated construction duration and additional travel costs were then input into the economic evaluation model. Output results represented the repair/rehabilitation plans that fit respectively the requirements of lowest total cost and shortest construction duration (see Figure 6).

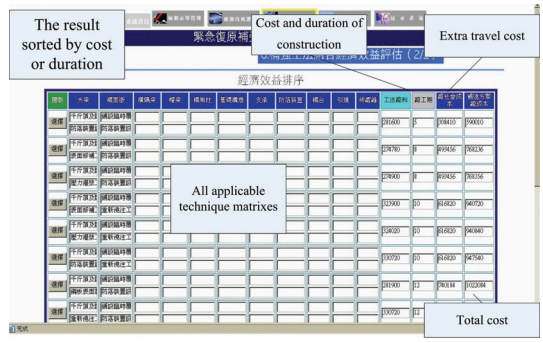


Figure 6 Result of Economic Evaluation Model

6. CONCLUSIONS

This research uses data and information from established disaster response procedures and a scientific approach to decide which among many potential emergency measures will most effectively achieve rehabilitation / reconstruction objectives. This research employed traffic assignment to calculate traffic flow changes and integrated user cost formulas to compute additional

travel costs. The Economic Evaluation model was developed to combine the consideration of repair/rehabilitation costs and travel cost to identify a repair/rehabilitation approach that maximizes benefit.

This paper describes a system architecture prototype for a web-based economic evaluation system that permits a user to access services anywhere via an internet-connected PC and helps decision makers enhance the effectiveness of repair/rehabilitation plans.

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INVESTIGATION OF AN AHP BASED MULTI CRITERIA WEIGHTING SCHEME FOR GIS ROUTING OF CROSS COUNTRY PIPELINE PROJECTS

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ABSTRACT

Pipelines are the most efficient, cost effective and environmentally friendly means of fluid transport [1]. When selecting the route of a cross country pipeline, the goal is to route it so that it has the greatest utility to the public while minimizing negative impacts to people and the natural environment. In order to accomplish this goal of addressing several factors, a large amount of location based information needs to be analyzed. Hence the manual routing processes are very tedious in nature. The advent of new techniques like that of Geographic Information System (GIS) has made the routing process of pipelines more systematic and effective.

This work identifies the various factors which need to be considered while routing a pipeline in the Indian scenario. A GIS to represent the various factors and automatically route the pipeline has been developed. A main drawback in the system is the lack of a structured methodology to derive the relative preferences of the different factors affecting the route. To address this issue, an AHP based methodology was developed. The GIS and the AHP methodology have been tested on case studies in the Indian scenario.

KEYWORDS

Analytical Hierarchy Process, Geographic Information Systems, Least Cost Path, Pipeline Routing, Weighting systems.

1. INTRODUCTION

Throughout the world, a large network of pipelines transports oil, gas, water and other products. Transmission or trunk pipelines are examples of engineering marvel requiring large investments, long gestation periods and operating life. This inexpensive, reliable and high capacity transport is critical to national economy and security [1].

Pipeline alignment is an optimization between several factors such as social issues, environmental issues, cost of the project and so on. Manual pipeline routing uses available maps, surveys and experience and is seriously constrained due to lack data handling capabilities. GIS techniques have an edge over the conventional methods in terms of speed of processing and analytical capability.

Further more, there is a distinct lack of a structured methodology to arrive at weightages for the factors affecting the pipeline route. In previous works, the weighting of factors has been done based on experience of the design team. It was found that there was a lack of a formalized decision making methodology that enabled analytical tradeoffs to be made.

The objectives of this work were:

- To identify the different factors affecting the routing process in the Indian scenario and to develop a GIS to route a cross country pipeline.
- To investigate an AHP based approach to elicit expert opinion to derive weightages for the factors affecting the route.
- To utilize these weightages in the GIS solution and to implement this system in case studies in the Indian scenario.

2. LITERATURE REVIEW

Luettinger et al. (2005) brings out the importance of the stakeholders perspective in the routing process [2]. They mention that the construction of a large-diameter transmission pipeline through heavily developed cities will create many challenges. There will be many engineering obstacles, environmental issues, construction issues, and general public concerns related to the construction of a pipeline of this size and length. Feldman et al. (1995) point out that the factors influencing pipeline route selection are technical and engineering requirements, environmental considerations, and population density [3]. Delavar et al. (2000) applied the least cost pathway analysis for the route selection process [4].

The critical issue in the GIS methodology is assigning the weights to the factors affecting the pipeline route. Edlin (2004) points out that, Geographic information systems (GIS), Multi-criteria decision making (MCDM), and Expert Systems (ES) techniques have been used in resolving the problems of lack of transparency in the weighting process [5]. Huang (2004) has demonstrated that AHP can be used Hazardous material routing [6].

3. SOLUTION METHODOLOGY

The GIS based approaches for pipeline routing process utilize relative rankings and weights on considering factors affecting the potential routes. Prior to the actual route design, corridor selection needs to be done [7]. The area to which the proposed pipeline should limit is first identified for collecting and assembling data like aerial photography, building/house location, existing utilities etc.

The base maps for the corridor selected are collected and the derived maps are generated. Once the derived maps are ready, the suitability analysis is done and a route is found abiding by the governing criteria.

Fig 1 shows the schematic representation of the methodology. Each of the components has been discussed in detail.

3.1 Selection of Factors Affecting the Route

The first step in a routing process is the selection of the factors affecting the pipeline route. Several spatial and non spatial factors affect the pipeline route.

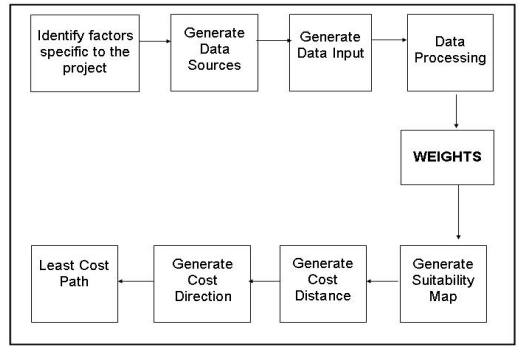


Figure 1 Schematic Representation of the Methodology

When a new routing process is initiated, the list of multiple criteria variables has to be decided first and then the criteria by which these variable constraint the routing process. The criteria refer to the rules which the route should abide to. In general the following factors were found to be more important and are addressed in greater detail in this work.

- Avoid areas with steep slopes
- Avoid road crossings, but proximity to the roads should be high
- Avoid railway crossings
- Avoid river crossings
- Avoid prohibited areas (Cities, Towns, Reservoirs and so on)
- Avoid reserved forest areas
- Avoid areas with high land cost
- Avoid unfavourable soil type

3.2 Data Sources

Maps, satellite imagery and aerial photography are required to make decisions for the route alignment. In the event of maps not being available, field surveys have to be employed and data about the target area should be collected. In this work, the topographic sheet numbers were first identified using the meta server of Survey of India and the required toposheets were procured from them. By visual examination of the target area, the corridor that was most suitable for pipeline routing was identified.

3.3 Data Input

The topographic maps of the area have to be scanned, geo referenced and prepared for further analysis. All spatial features such as roads, rivers, railway lines, town limits and so on have to be digitized for further processing.

3.4 Data Processing

The digitized layers are to be processed so that the route abides the criteria mentioned above. Data processing is done based on the type of spatial attribute. Therefore, we can have

- Processing line features
- Processing polygon features

Figure 2 shows the overview of processing of some features. The first step in data processing is converting the vector data to raster. This is followed by calculating the feature distance cost. (Feature distance cost refers to the weighted cost as one moves away from the feature) This is very important is the processing of features such as roads, land cost polygons and so on. The final step is reclassification.

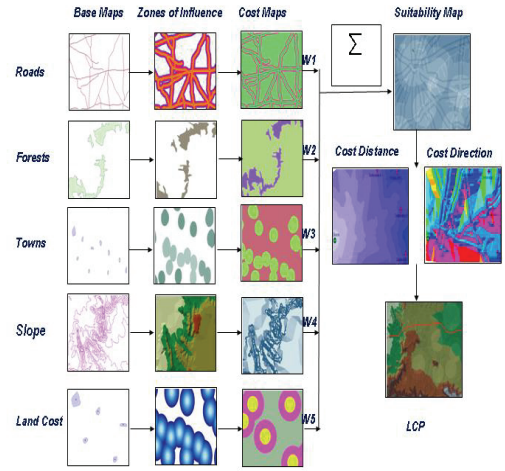


Figure 2 Overview of the Solution Methodology

3.5 Assigning Weights to the Variables

A weighting system has to be devised for weighing each of the map layers. The weighting system forms the backbone of the methodology. The weighted layers are all summed up to form the suitability layer. This layer forms the basis of the GIS analysis. The Analytical Hierarchy Process has been used to derive weightages for the thematic layers. The suitability layer is analyzed for the optimal route. The AHP has been discussed in detail in the next section.

3.6 Raster Data Analysis

The final step is to apply the least cost path procedure and find out the optimal route.

According to Berry J. K. [7], the steps in implementing the LCP are as follows:

- To develop a discrete cost surface that indicates the relative preference for routing at every location in a project area,
- To generate an accumulated cost surface characterizing the optimal connectivity from a starting location (point, line or area) to all other locations based on the intervening relative preferences,
- To identify the path of least resistance (steepest downhill path) from a desired end location along the accumulated surface.

4. THE ANALYTICAL HIERARCHY PROCESS

Analytical Hierarchy Process (AHP) is a quantitative method for ranking decision making alternatives by developing a numerical score to rank each decision alternative based on how well each alternative meets the decision maker's criteria [8].

The AHP is a decision-making approach developed by Saaty in 1980. The process aids in the solution of complex multiple criteria problems in a number of application domains. In AHP, one constructs hierarchies, then makes judgments or performs measurements on pairs of elements with respect to a control element to obtain ratio scales which are then incorporated into the whole structure to select the best alternative.

The three basic steps for considering decision problems by AHP are:

- Construction of a structural hierarchy
- Establishment of comparative judgments
- Synthesis of priorities

4.1 Establishment of Comparative Judgments

A decision maker or an expert needs to be provided with pair wise assessments of all the variables affecting the routing process to establish a preference matrix, the synthesis of which will result in weightages for the multi criteria variables.

A questionnaire (Fig 3) with all the pair wise comparisons can be presented to an expert. The expert responds to a pair wise comparison, by returning the relative importance of the two criteria on a scale that has been proposed by Thomas L Saaty.

AVOID	RHS* criteria more important than LHS* criteria									LHS* criteria more important than RHS* criteria									AVOID
Steep Slopes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Road Crossings
Steep Slopes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Railway Crossings

Figure. 3 An extract of the Primary Questionnaire to Gather Expert Opinion

The responses are consolidated in a preference matrix and synthesized to obtain the weightages.

4.2 Drawbacks in the Application of AHP

Previous works on this topic have failed to incorporate the sub classes of a particular criterion in the routing process. Example: Roads are considered as one criterion and the subclasses of roads such as metalled roads, unmetalled roads and so on have not been considered. This is evidently not a correct practice as the influence exerted by each sub class will be different from another.

The difference in the influence exerted by each sub class can be explained with the aid of the following example. Consider the case of Railway lines in which the expert cannot definitely say that all the sub classes of the road layer i.e. Avoiding National Highway, Metalled, Unmetalled and Cart tracks are more important than avoiding railway lines. There will be a transition point where in the constituents of one criteria will start becoming less important when compared to the other criteria or vice versa Ex: Avoiding a National Highway is more important than avoiding a Railway crossing, but avoiding a railway line is more important when compared to a cart track. Hence there is a transition.

It was found that that the conventional way of gathering pair wise comparison for AHP model cannot be implemented as the result of the pair comparisons being very large in number. This in turn will make the expert's job of answering the questionnaire very cumbersome. Inconsistency in judgments might creep in as a result. Therefore the need to modify the methodology of gathering expert opinion arises.

4.3 Modified Approach to Establish Comparative Judgments

To resolve the problem highlighted in the previous section, it was necessary to modify the existing procedure to collect pair wise judgments from the expert. Hence a second questionnaire (Fig 4) was designed to supplement the information obtained from the main questionnaire.

Criteria	Importance w.r.t National Highway	Is Criteria more important than Railway Crossings (based on Traffic conditions/train freq) (Yes or No)	AHP Scale
National Highway	1		
Metalled Roads			
Unmetalled Roads			
Cart Tracks			

Figure 4 Secondary Questionnaire

In the modified procedure, the expert, first needs to quantify the importance of the sub classes w.r.t the parent criterion as a fraction of 1. Example: The importance of Metalled roads w.r.t National Highways is 0.6.

The subclasses are now compared against other criteria and the expert will judge the comparisons in the form of a Yes or a No. If the expert response is Yes, then the AHP scale value for that criterion can be calculated by multiplying the AHP scale value of the parent criterion with the relative importance value. If the user response is a NO, then the expert is asked to provide the AHP scale value for that particular comparison. When the expert response changes from a YES to a NO, the transition point can be observed.

The AHP scale values are consolidated in the preference matrix and the basic AHP routine is performed to obtain the weightages. The preference matrix will also contain pair wise comparison between the sub classes. Hence the pair wise assessments for those comparisons also have to be obtained from the expert.

5. IMPLEMENTATION OF THE METHODOLOGY

The methodology implemented in the following sequence:

- Data Input
  - Acquiring topographic maps of the target area
  - Acquiring satellite imagery of the area
  - Identification of factors affecting the route.
  - Creating new layers for the analysis
- Data Analysis
  - Vector Data Analysis: Processing the data, weighting and Overlay
  - Raster Data Analysis: Suitability layer, Cost distancing and Cost direction

The methodology was implemented on a practical problem in the Indian scenario. This problem was a live project of Larson & Toubro (ECC). Arc GIS 8.1 was used for the processing geo spatial information.

Criteria	Importance w.r.t National Highway	Is Criteria more important than Railway Crossings (based on Traffic conditions/train freq) (Yes or No)	AHP Scale
National Highway	1	Y	9
Metalled Roads	0.6	Y	9* 0.6 = 5
Unmetalled Roads	0.4	N	8
Cart Tracks	0.2	N	9

Figure 5 Secondary Questionnaire with Sample Expert Opinion

5.1 The Weighting System

A weighing system was developed using the Analytical Hierarchy Process for the case study. A questionnaire was designed to present all the pair wise comparisons of the criteria to the expert and a numerical scale has been provided, so that expert and quantitatively could rank one criteria over another and establish the comparative judgments. A sub questionnaire was also designed to counter the effect of variation in the different classes of the criteria. The questionnaire developed was developed was presented to 3 experts from Larson & Toubro (ECC), India. The AHP process was automated using VBA in MS EXCEL environment for synthesis of the comparative judgments. The pair wise comparisons of the criteria serve as input to the VBA module. The VBA module was programmed to display the weightages in graphical format.

6. RESULTS AND DISCUSSION

6.1 Results Obtained from the AHP Module

The weightages derived for the input datasets by collecting expert opinions from experts at Larson

& Toubro (ECC) are presented in the following table. Inconsistency ratio was 0.363. Hence the judgments can be considered fairly consistent

Table 1 Weightages for the Input Datasets

	Expert 1	Expert 2	Expert 3	AVERAGE
Slopes	0.0420	0.0640	0.0306	0.0455
NH	0.0463	0.0679	0.0991	0.0711
Metalled	0.0232	0.0246	0.0414	0.0297
Unmetalled	0.0143	0.0095	0.0117	0.0118
Cart Roads	0.0101	0.0095	0.0090	0.0095
Railways	0.0842	0.0933	0.1352	0.1042
Rivers	0.1335	0.1584	0.1072	0.1330
Prohibited	0.2368	0.2437	0.1539	0.2115
Forest	0.2368	0.2097	0.2005	0.2156
LandCost	0.0688	0.0775	0.1614	0.1026
Soil	0.1042	0.0419	0.0500	0.0654

6.2 Results and Analysis of Least Cost Pathway Analysis

The suitability map, cost distance and direction rasters were obtained. The routes obtained by are displayed over the DEM of the area.

The methodology was first implemented without using any weightages to make a comparison between a non AHP aided approach and an AHP aided approach. The results (Fig 6) clearly bring out the difference in the two routes, thus highlighting the importance of the weightages. The non AHP aided route was found to have cut across a prohibited area which is unacceptable. When weightages are implemented, the methodology is able to correct to route as per the defined criteria.

7. CONCLUSIONS

From this study conclusions can be made in the following areas:

7.1 Multi Criteria Weighting for Pipeline Routing

- The Analytical Hierarchy Process to derive weightages and the GIS methodology to route the pipeline have been successfully integrated.
- It was also noticed that the mode of gathering expert opinion for the AHP model could not be implemented in its conventional form, because it could not incorporate the sub classes of particular criteria. An attempt to do so would have resulted in the making the expert's job of assessing the pair wise comparison too tedious.
- Therefore an AHP model with a modified procedure to collect expert opinion has been successfully implemented in the case study and its results show that it clearly scores over the conventional method of gathering pair wise comparisons.
- The results of the case studies also support the fact that this study has been able to emulate the expert decision making capability.

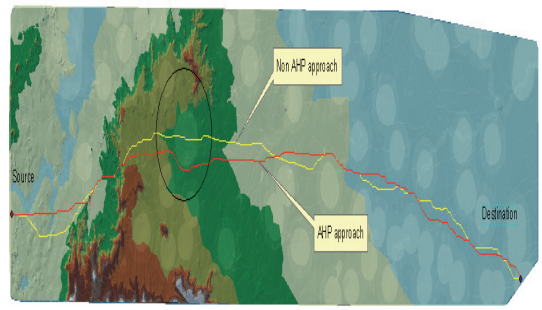


Figure 6 Comparison between Routes Obtained - AHP approach and Non AHP Approach

7.2 Conclusions from the Case Study in the Indian Scenario

- The route suggested by this methodology cannot be considered as the optimal route. This is because of the fact that there are several other ground realities that affect the route. These ground realities can be ascertained only after a detailed ground survey is made.
- The route suggested by this study serves as an excellent aid for the execution team to make the preliminary changes and report the ground realities affecting the proposed route. The design team can then incorporate changes and arrive at a route which can then be considered optimal. Thus the results of this study help immensely in reducing the numerous options for the design and the execution team.
- The results of this study clearly demonstrate the benefits of integrating GIS and AHP, the combination of which,

served as a decision support system for the pipeline routing process.

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OPTIMUM EVACUATION IN PUBLIC GATHERING PLACES DURING THE TIME OF DISASTER

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ABSTRACT

Urbanization is rapidly increasing all over the world. Past 2 decades in India, many cities have attracted large population. Reasons being the belief of better education, health care, job/business prospects, etc. For meeting the demands of population density, many high-rise structures and large public gathering places are emerging in cities. Places where few thousands of people can meet are quite common in major cities. It is due to this reason, evacuation at the public gathering places has gained a lot of importance.

Though some traditional hand calculation procedures are available for the estimation of evacuation time, we have attempted to simulate the same in more realistic and reliable way by using latest computational techniques. In this paper, we developed a procedure to calculate the optimum evacuation time by taking input parameters like dimensions of the building, number of doors, size of doors, number of people and seating arrangement. This tool will help architect in efficient design of a public gathering place.

KEYWORDS

Building Evacuation, Public Gathering Places, Disaster, Simulation and Optimum Time

1. INTRODUCTION

Urbanization in India is rapidly increasing, considering infrastructure wise big shopping complexes, theaters, auditoriums and many other building and facilities are getting bigger and bigger and attract more and more people. These crowds have to be routed through the building in an efficient manner especially at the disaster times.

These days optimum evacuation is being given more and more importance in light of recent disasters like fire accidents at public gathering places few examples are on 16th July 2004 "83 children killed in school fire in Kumbakonam" [1], on 3rd February 2004"Srirangam wedding tragedy, which cost 62 lives because of fire accident in the marriage hall"[2], on May 22, 2005 "Bomb explosions rocked two cinema halls in Delhi injuring at least 40 people"[3].There are many instances in the history involving trampling and crushing occurred in crowded places due to emergency evacuation. Through the studies of evacuation we can hope to design smarter spaces and identify problem areas. At last it is all about to design safer and more efficient buildings, concert halls and other public gathering places.

Although the regulatory provisions governing egress design are prescribed, the actual performance of the evacuation systems is difficult to asses. There have been numerous incidents reported regarding over crowding and crushing during emergency situations occurring in sport stadiums, theaters, social gathering places and other facilities.

The shape of a particular building, parameters like size, number and location of doors has much to do with congestion and crowding. Studies are still going on to improve public safety in public

gathering places involving many disciplines architectural design for safe evacuation, crowd planning and management, crowd simulation, emergency planning and many others.

Applying that knowledge in the design of buildings has the potential to lead to optimized designs in terms of the level of safety, architectural freedom and costs. Traditional building rules targeting safe evacuation are however in most cases based on a much simplified model of the evacuation process, which does not allow the use of the currently available knowledge and technology.

In this research, using the currently available knowledge and latest technology we have developed a tool to calculate the optimum evacuation time of a particular building plan changing factors like number of persons, parameters of the building like number, size, and location of doors, which can also simulate the movement of public during the evacuation at normal and emergency conditions.

2. REVIEW OF EXISTING EVACUATION MODELS

Before embarking on this discussion it is useful to review the past and current models, one of the essential concepts of safety in buildings is the rapid and adequate evacuation of all the occupants of the building in case of any accident. For example many of the safety measures introduced in the design and operation of the building are aimed at ensuring that the occupants can safely leave the building before they are over taken by heat and toxic products and before the building collapses, and for this many models have been developed to find the evacuation time of a particular building, congestion areas, bottle necks and other parameters adding for improper evacuation.

To achieve a more realistic evacuation calculation, engineers have been looking to evacuation computer models to assess a building's life safety. Currently, there are a number of evacuation models to choose from, each with unique characteristics and specialties.

Few of the models which are currently available to the public are FPETool[6], EVACNET4[7,8], TIMETEX[9], WAYOUT[10], STEPS[11,12], PEDROUTE / PAXPORT[13,14], ASERI[15], building EXODUS[16], EXITT[17,18], models available on consultancy basis are PathFinder[19], EESCAPE[20], Myriad[21,22], there are other models which have not yet been released and others which are no longer in use.

And each model has at least one of these special features like Counterflow, Manual exit block/obstacles, Fire conditions affect behaviour, Defining groups , Disabilities/slow occupant groups, Delays/pre-movement times, Elevator use, Toxicity of the occupants, Impatience/drive variables, Route choice of the occupants/occupant distribution.

These models have been categorized using primary category labelled modelling method, it describes about the calculation of evacuation times for buildings like behavioural model incorporates decision making by occupants or actions that are performed due to conditions in the building. Movement modelling shows the occupants move from one point to another point, exit or place of safety, key in showing congestion areas, queuing or bottlenecks with in the simulated building. Partial behaviour models primarily calculate occupant movement, but begin to simulate behaviours. Possible behaviours could be implicitly represented by pre-movement time distributions among the occupants, unique occupant characteristics, overtaking behaviour, and the introduction of smoke or smoke effects to the occupant. These are models capable of simulating an entire building, and occupants' movements throughout the model are based on observed human behaviour data.

Purpose of the model as it pertains to certain building types, models that can simulate any type of building, models that specialize in residences, models that specialize in public transport stations, models that are capable of simulating low-rise buildings only and models that only simulate 1-route/exit of the building.

A fine network model divides a floor plan into a number of small grid cells that the occupants move to and from. The coarse network models divide the floor plan into rooms, corridors, stair sections, etc. and the occupants move from one room to another. A continuous network model applies a

2D (continuous) space to the floor plans of the structure, allowing the occupants to walk from one point in space to another throughout the building.

Perspective of the model explains how the model views the occupants and how the occupants view the building. Two ways that a model can view the occupants are globally and individually, they are differentiated by tracking movement of individual or a homogeneous group of people moving towards the exits. Individual perspective of the occupants is more detailed as we can know the position of each occupant throughout the simulation. The occupant can view the building in either a global or individual way. An occupant's individual view of the building is one where the occupant is not all knowing of the building's exit paths and decides his/her route based on information

Behaviour of the occupants is represented in many different ways like No behaviour denotes that only the movement aspect of the evacuation, Implicit behaviour represents those models that attempt to model behaviour implicitly by assigning certain response delays or occupant characteristics that affect movement throughout the evacuation, Conditional behaviour reflects models that assign individual actions to a person or group of occupants that are affected by structural or environmental conditions of the evacuation, Artificial Intelligence resembles the models that attempt to simulate human intelligence throughout the evacuation, Probabilistic represents that many of the rules or conditional-based models are stochastic, allowing for the variations in outcome by repeating certain simulations.

Movement one of the main factors refers to how the models move occupants throughout the building. In most of the models occupants are usually assigned a specific velocity by the user or modelling program. The differences in the models occur when the occupants become closer in a high density situation, resulting in queuing and congestion within the building. Few of them are Density correlation model assigns a speed and flow to individuals or populations based on the density of the space, User's choice where user assigns speed, flow, and density values to certain spaces of the building, Inter-person distance where each individual is surrounded by a 360 "bubble" that allows them only a certain minimum distance from other occupants, obstacles, and components of the building, Potential in which each grid cell in the space is given a certain number value, or potential, from a particular point in the building that will move occupants throughout the space in a certain direction. Occupants follow a potential map and attempt to lower their potential with every step or grid cell they travel to.

Visualization identifies whether the model allows the user to visualize the evacuation output from the structure. Visualizations of the evacuation allow the user to see where the bottlenecks and points of congestion are located inside the space. Many of the models allow for at least 2-D visualization (2-D), and recently more have released versions or collaborate with other virtual programs that will present results in 3-D (3-D). Other models do not have any visualization capabilities.

As time passes, more evacuation models will be developed and many of the current models will be updated by developers.

3. PROPOSED MODEL

The model developed attempts to take into consideration of building parameters

1) Number of doors
2) Location of doors
3) Size of doors
4) Number of occupants in the building.

This model tracks the trajectory of each individual as they make their way out of the enclosure or are over come by accidents in the building.

This model is designed to calculate the optimum time of evacuation and also to simulate the evacuation of large numbers of people from a different variety of enclosures. This time is calculated by changing parameters of the building. The model developed using object oriented techniques is based on rules. The progressive motion of each individual is being determined by a set of rules.

The figure-1 shows the total working process of the proposed model.

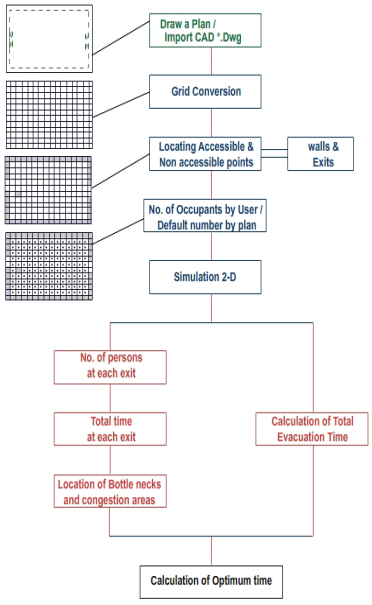


Figure 1 Work Flow Diagram

This model uses fine network which can effectively describe the movement pattern of each individual in a building. Such information can be adapted to a virtual reality presentation that can help building designers in presenting their design effectively. This can also model the relative coordinates of each individual at any point of time. It can effectively handle the individual and crowd behaviour.

The model developed uses the information from the user to draw the plan of a building in terms of walls, columns, other obstacles as inaccessible points and doors as accessible points. Now the total plan is divided in to small grid cells which can be occupied by a person. Number of occupants can be mentioned by the user in terms of percentage or else default number of occupants is taken according to the number of accessible grid cells.

Each occupant in the building is represented by an agent who has special properties:

1) Constant speed of 1.27 m/s,

2) Only one agent can occupy each grid cell at any point of time.

3) Takes individual decision.

4) Analyze the situation

5) The default grid cell size is 0.25 m by 0. 25 m as the cell size can be changed by the user.

In high density situation or queuing, the movement speed is affected by the availability of the next grid cell, individual agent has eight possible decisions surrounding the grid cell as shown in the fig-2 and the decision of where to go is based on which of the adjacent grid cell is nearer to the exit, in case of more than one grid cell availability, random function is used to choose the next grid cell.

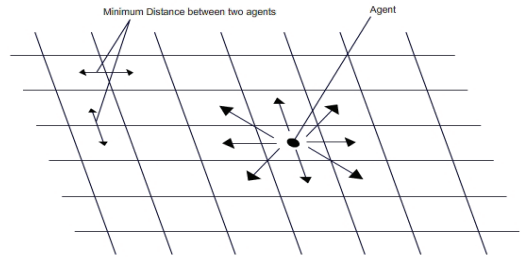


Figure 2 Computer Agent

A concept of multi-agent based computational system has been prototyped, which is able to demonstrate some emergent human social behaviors, such as competitive behavior, queuing behavior, herding behavior, and bi-directional crowd flow through simulating the behavior of human agents.

2-D Simulation is one of the important factors which show the actual movement of occupants during their evacuation and also shows the places of congestion bottlenecks throughout the building, which can be well designed.

The fig-3 shows the snapshot of the proposed model which has the input parameters dimensions of the plan, number of doors, location of doors and number of occupants. After the simulation is completed the data we have are number of persons at each door, total time taken at each door and total time of evacuation.

Now optimum time is calculated for the different combinations

1) Location of doors are changed
2) Number of doors are changed
3) Sizes of doors are changed
4) Number of occupants are changed

For all the above combinations graphs are plotted against time and optimum time is calculated.

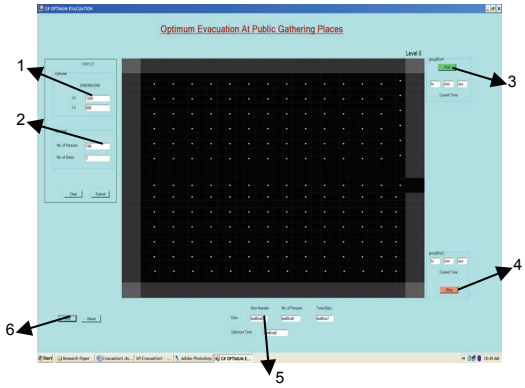


Figure 3 Proposed Model

INPUT AND OUTPUT FROM MODEL

1) Dimensions of the room (I)
2) Number of persons (I/U)
3) Timer start (O)
4) Timer stop (O)
5) Given door number (I) will get number of persons (O), time for that particular door (O)
6) Exit and Reset (U)

(**I**-input, **O**-output, **U**-user)

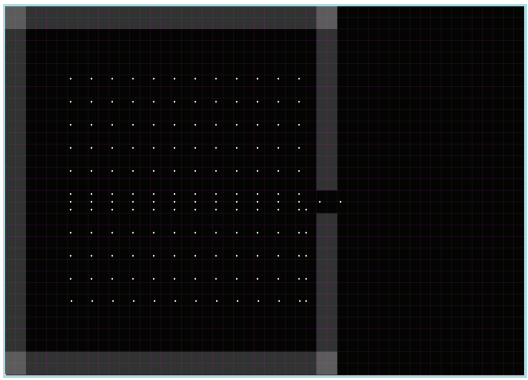


Figure 4 Proposed Model

Fig.4 shows the graphical area when the dimensions are changed. Figure also shows the movement of the agents to the door. The number of doors given during the compilation is one door. The numbers represented on the Fig.3 from 1 to 6 gives the details of the proposed model Input, Output or User.

4. RESULTS AND DISCUSSION

The output file for proposed model is shown in the fig-5 and consists of model dimensions, agent speed, number of floors, door width, number of persons from each door and time duration.

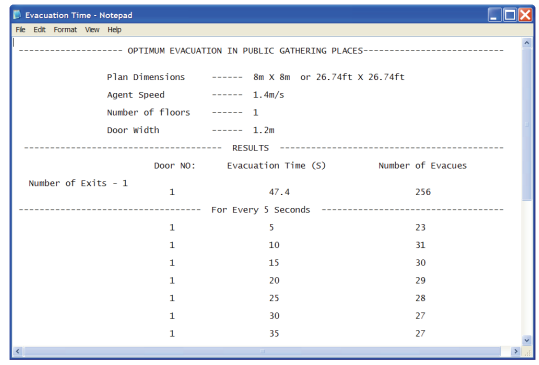


Figure 5 Output File

There are many situations where proper or improper planning can effect all of us in our day to day lives: complexes and residential buildings, outdoor arenas, and more.

Apart from calculating optimum evacuation time for the present existing plans, the model also calculates optimum evacuation time by slight variation in building parameters. As we can see from fig-6 the parameters of the building are directly proportional to the time of evacuation and cost of project, this can be a secondary factor which can be considered for optimum cost of the project too.

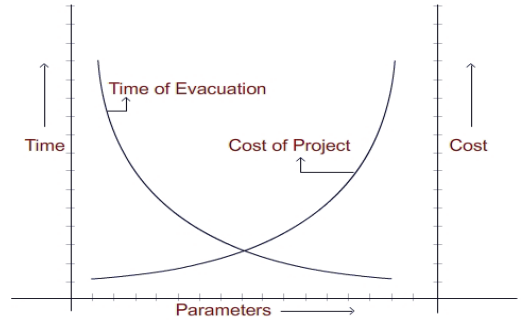


Figure 6

5. CONCLUSION

The model presented, when properly applied and provided for can help with a greater understanding of occupant's movement at any public gathering places and indeed can help architects for better designs.

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MODIFIED SIMULATED ANNEALING ALGORITHM AND MODIFIED TWO-STAGE SOLUTION FINDING PROCEDURE FOR OPTIMIZING LINEAR SCHEDULING PROJECTS WITH MULTIPLE RESOURCE CONSTRAINTS

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ABSTRACT

This paper presents a modified two-stage solution finding procedure and some modified simulated annealing algorithms to optimize linear scheduling projects with multiple resource constraints and their effectiveness is verified with a proposed problem. Simulated annealing and improved simulated annealing are compared in the same condition. The Reasons of obtaining improvement by modified simulated annealing is explained briefly too.

KEYWORDS

Modified Simulated Annealing, Modified Two-Stage Solution Finding Procedure, Linear Scheduling, Multiple Resource Constraints

1. INTRODUCTION

Combinatorial optimization is widely used these days for engineering purposes and one of its applications is optimization of linear projects. Linear construction projects such as tunnels contain repeated activities at different locations. CPM is not an effective method for scheduling linear projects, so other methods such as Linear Scheduling Method (LSM) have been developed. Practically, resources are limited in construction projects so multiple resource constraints are incorporated in the model by"resource leveling" and "resource allocation". Optimizing linear scheduling projects with multiple resource constraints is a combinatorial optimization problem, so it should be optimized by one of the combinatorial optimization tools. Modified simulated annealing is chosen for this goal in this paper and it is compared in the same circumstances with simulated annealing to show its effectiveness.

2. LITERATURE REVIEW

LSM was introduced by Johnston in 1981 [1] in a highway construction project and simulated annealing is introduced in 1983 in the science magazine [2] in 1983. Harmelink (1995) [3] established a heuristic algorithm to determine the controlling activities path but without consideration of resource limitations. Mattila (1997) [4] considered resource leveling in a model of highway construction project. He solved the model by using mixed integer programming. Liu (1999) [5] considered single resource allocation and proposed a heuristic solution procedure using the Tabu Search algorithm in his model. The model included two stages. Lue & Hwang (2001) [6] proposed a precast production project and solved it with a genetic algorithm-based model. Finally Chung-I Yen (2005) [7] proposed simulated annealing for optimizing linear scheduling projects with multiple resource

constraints. He considered resource allocation and resource leveling simultaneously.

Although the proposed models are useful, there are some modifications which can be done to make the models more realistic and easier to use. This paper discusses three modifications and the effectiveness of them is examined too.

3. PROBLEM OBJECTIVES

Assume there is a linear project with N activities, M locations, and I critical resources. The objectives are as following [7]:

$$Minimize Max\{f(n,m) | n = 1..N; m = 1..M\} \quad (1)$$

$$Minimize \sum_{t=1}^{T-1} \sum_{i=1}^{I} w_i (dp_{t,i} + dm_{t,i}) \quad (2)$$

There are some other equations which should be satisfied but they are not the main objective. Some of them are introduced here

Constraints:

- Activities precedence relationships
- Resource availability
- Activities completion
- Resource usage deviation

Notations:

$dp_{t,i}$: Absolute difference plus value of resource I assignment between day t+1 and day t

$dm_{t,i}$: Absolute difference minus value of resource I assignment between day t+1 and day t

w_i : Weighting factor for resource i

4. MODIFIED SOLUTION METHODOLOGY

A two-stage solution-finding procedure is introduced in this section and two possible modifications are discussed too.

Stage one begins with solving the problem without resource constraint. A linear scheduling diagram will be drawn too. Then the problem will be solved by multiple resource allocation algorithms. It is assumed that resources are fixed for an activity in all locations. NTF concept is utilized in solving by considering multiple resource constraints. Stage one demand a time-consuming work; so a simple feasible solution for it is proposed in this paper. In this method we imagine that activities don't have any overlapping so the first activity of the project in all locations should be finished before the second activity with the second priority starts and it continues till the project is finished. In the other words, it is the maximum duration for the project but it guarantees that we have enough resources for activities to be done. It is assumed that resources are fixed for an activity in all locations in this stage. The effectiveness of this approach is examined later in this paper.

Simulated annealing is used during the second stage to find the optimized solution. The number of one of the resources of one of the activities is changed during each iteration of the algorithm to find the best allocation. The problem will be solved by multiple-resource allocation algorithm. NTF concept is utilized in solving by considering multiple resource constraints. The resources assigned to a repetitive activity can be varied at different locations within a specified range. The goal is to find best assignment of resources to activities and the best sequence of activities to have the minimum duration and fluctuation of resources assigned for a project. In the proposed models [7], having the minimum duration is the first objective and when only two projects have the same duration, the second criterion is considered. So we can conclude that fluctuation is a passive criterion. It is the location of the second modification. Most projects have a deadline. In the modified algorithm, the priority of objectives is not fixed and it depends on the deadline of the project. When the durations of comparing projects are more than the deadline, the duration objective has the priority and when the durations are less than the deadline, the fluctuation has the first priority. Search neighborhood is all possible resource assignments to activities. The maximum and minimum temperatures are 1000 and 1 respectively.

5. MODIFIED SIMULATED ANNEALING

Simulated annealing is based on the similarity between solid annealing process and combinatorial optimization. The algorithm consists of several decreasing temperatures.

Simulated annealing algorithm utilizes acceptance probability which helps it to escape from being trapped in local solution. The chance of acceptance of new solution is high at high temperatures and this chance reduces when temperature decreases. It is because the fact that the chance of being trapped in a local solution is high during first temperature steps. It works more random at the beginning and gradually turns into a more traditional local search algorithm [7].

Although the chance of being trapped in a local solution is high at the beginning, there is no need to have a certain iteration number. It can be less at the beginning and higher at the higher temperatures. It is because the fact that it is seen that the solution in higher temperatures is among last iterations while the solution in lower temperatures doesn't follow a fixed rule. It can be reduced with a lot of schemes but gradual reduction has been used in this paper. Geometric, arithmetic and logarithmic improvements [8] are presented in this paper.

Simulated annealing and modified simulated annealing algorithms test some feasible solutions to find the most optimized solution. It is needed to have the same number of testing to be able to compare them and show which one is more powerful. Number of testing of feasible solutions can be calculated as following.

$$N = \sum_{t=1}^{t_{\max}} N(t) \tag{3}$$

where N is the number of testing of feasible solutions, t is the number of times that temperature has been decreased which can be a number between 1 and t_{max}, and t_{max} is the maximum number of times that the temperature has been changed.

Modifications are provided in three categories which are discussed later and corresponding computations are presented for each one but first it is needed to compute the number of testing for the non-modified simulated algorithm with a fixed number of iterations in each temperature. The following formula calculates the number of testing of feasible solutions for a simulated annealing with a fixed number of iterations in each temperature.

$$N = N_f \times t_{\max} \tag{4}$$

where N_f is the number of iterations in each temperature which is fixed. For example, suppose that the initial temperature is 1000, the minimum temperature is 1, the number of iterations in each temperature is fixed to 1000, and the cooling ratio is 0.1. In this algorithm, the maximum number of times that temperature has been changed is 70, so the number of feasible solutions which are tested is 70000. The number of feasible solutions which are tested in the other algorithms must be 70000 to be able to show the probable advantages of them over the standard simulated annealing. The following subsections elaborate three methods to improve simulated annealing.

5.1 Geometric Improvement

In this method, the number of iterations in each temperature geometrically increases as t rises. Equation (5) represents the gradual reduction of iterations.

$$N(t) = t \times x \quad | \quad t = 1...t_{\max} \tag{5}$$

The number of testing of feasible solutions can be easily computed with (6).

$$N = \sum_{t=1}^{t_{\max}} N(t) = x \times \left({(t_{\max} + 1) \times t} \big/ {2} \right) \tag{6}$$

where x is the parameter of geometric improvement which should be calculated for each specific example if the goal is comparison of this modification with the other methods. For instance, the following equation calculates x in order to have the same number of testing for the above-said example in which t_{max} was 70 and the number of testing of feasible solutions for a non-modified simulated annealing was 70000.

$$x \times {(71 \times 70)} \big/ {2} = 70000 \quad \rightarrow \quad \text{x=28.17}$$

5.2 Logarithmic Improvement

The number of iterations in each temperature logarithmically increases as t rises. (7) and (8) represent this method.

$$N(t) = x \Big/ \log(T(t)) \quad | \; t = 1 \ldots t_{\max} \tag{7}$$

$$N = \sum_{t=1}^{t_{\max}} N(t) = \sum_{t=1}^{t_{\max}} \left(x \Big/ \log(T_{\max} \times e^{(-t*0.1)}) \right) \tag{8}$$

where T(t) is temperature as it has been changed t times and T_{max} is the maximum temperature. x can be calculated for above-said example.

$$\sum_{t=1}^{70} \left(x \Big/ \log(1000 * e^{(-t \times 0.1)}) \right) = 70000 \rightarrow \text{x=18}$$

4.3

5.3 Arithmetic Improvement

The number of iterations in each temperature arithmetically increases as t rises. (3.10) and (3.11) and (3.12) represent this method.

$$N(t) = N(t-1) + x \quad | \quad t = 1 \ldots t_{\max} \tag{9}$$

$$N(1) = 10 \tag{10}$$

$$N = N(1) \times t_{\max} + x \times \left(\frac{t_{\max} \times (t_{\max} - 1)}{2} \right) \tag{11}$$

For example, x is computed for the above-said example as following.

$$10 \times 70 + x \times \left(\frac{70 \times (70-1)}{2} \right) = 70000 \rightarrow$$

$$\text{x} = 28.69$$

6. TEST OF THE MODIFICATIONS

The proposed problem is a part of a linear schedule. There are 6 identical semi-detached houses, so there are six locations. There are five repetitive activities which are flooring, utilities services, air-conditioning, painting and cleaning. Activities fight for two critical resources in the problem. The goal of this problem is to find the best resource assignment combination and the best sequence of activities to minimize the total project duration and the fluctuation of resource usage. The main objective is to find the minimum project duration. The second objective (minimum fluctuation of resource usage) is used when there are two schedules with the same duration. The following assumptions have been observed [7]:

1. A task can not be split. Once an activity is started, it will continue without interruption until it is finished.
2. Resources are limited. The limitation is assumed to be a constant across the entire project life span.
3. A resource con not be split.
4. Resources are assumed to maintain a constant productivity level within a certain range of assignment.
5. A resource can not be split.

Table 1 lists required information about the proposed artificial project and its activities. Table 2 presents information about two critical resources. The maximum number of resources 1 and 2 are 4 and 3 respectively.

Table 1 Required Information About the Proposed Artificial Project and its Activities

Activity (Description)	Duration (Days)	Predecessor
A (Flooring)	4	
B (Utilities services)	2	A (FS0)
C (Air conditioning)	2	B (FS0)
D (Painting)	2	C (FS1)
E (Cleaning)	1	D (FS0)

Table 2 Information About Two Critical Resources

Act.	L1	L2	Total L1 Required	Total L2 Required	Activity priority	L1 Range	L2 Range
A	3	2	4*3=12	4*2=8	1	2-4	1-3
B	2	1	2*2=4	2*1=2	2	1-3	1-2
C	2	1	2*2=4	2*1=2	3	1-3	1-3
D	1	1	2*1=2	2*1=2	4	1-2	1-2
E	1	1	1*1=1	1*1=1	5	1-2	1-2

Table 3 Average and Most Optimized Answer Which is Achieved from 100 Implementations

	Average	Most Optimized answer
Simulated annealing	46.42	43
Geometrically improved	45.01	42
Arithmetically improved	45.8	43
Logarithmically improved	44.77	41

Table 4 Results of 100 Implementations of the Program with Two Types of Initial Solution

	Carefully produced initial solution	Easily produced initial solution
Average	46.42	46.52
Most optimized answer	43	43
Variance	2.333	1.828

7. SUMMARY AND CONCLUSION

The problem is written in Java programming language. The written program is run 100 times for each of the following cases: no modification, modified simulated annealing, modified first stage and modified objective function. The following conclusions can be achieved easily from the results:

- Modified simulated annealing algorithms are significantly effective. The effectiveness is more highlighted when there is a real project with more activities, locations, and critical resources. Table 3 summarizes the results of implementations.
- There is not a significant change in the results of implementations when either the initial solution is simply produced based on the fact that activities should not have any overlapping or is intricately produced by multiple resource allocation algorithms. Table-4 depicts the results of 100 implementations of the program with two types of initial solution. It is due to the fact that simulated annealing and the model work somewhat randomly. Although the difference between results may be larger in multi-project or mega-project examples, the time which can be saved will justify using this approach. Table 5 shows a part of the conventional part to produce initial answer which is so time-consuming.
- The improved objectives of modified solution-finding procedure make the model more realistic

Table 5 Producing the Initial Solution for the First Stage

step	CT	NT	As	Ap	L1 available	L2 available	L1 assigned	L2 assigned	assigned	completed
1	0	4	A1	-	4	3	3	2	A1	A1
2	4	8	A2	-	4	3	3	2	A2	A2
3	8	12	A3	-	4	3	3	2	A3	A3
4	12	14	A4	-	4	3	3	2	A4	-
5	14	16	B1	A4	1	1	3	2	A4	A4
6	16	18	A5,B1	-	4	3	3	2	A5	-
7	18	20	B1	A5	1	1	3	2	A5	A5
8	20	22	A6,B1	-	4	3	3	2	A6	-
9	22	24	B1	A6	1	1	3	2	A6	A6
10	24	26	B1	-	4	3	2	1	B1	B1
25	47	48	E5	D6	3	2	2	2	E5,D6	E5,D6
26	48	49	E6	-	4	3	1	1	E6	E6

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OPTIMIZATION OF CONTRACTOR' S S-CURVE

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ABSTRACT

While striving to satisfy owners' needs, to minimize construction cost and pursue the maximum profits under a fixed contract amount and duration is always one of the most important objectives of contractors. Only a sound work plan, which includes optimal working sequences and perfect timing for executing each individual activity, can enhance the work efficiency and enable contractors to fulfill the contract at the lowest cost. This research develops a contractors' optimal S-curve model, which can optimize the allocation of resources along the project schedule, under major assumptions that for a specific task, there is a trade-off relationship in terms of work productivity between two different types of resources and there are costs for resource mobilization and demobilization. The S-curve established can be used as a baseline to measure the extra cost caused by changes and disruptions in the course of construction and the overall project performance at the completion of the project.

KEYWORDS

S-Curve, Optimization, Resource Allocation, Genetic Algorithms

1. INTRODUCTION

Conventionally, S-curve has long been adopted as an important baseline in project control system to monitor the project performance. Most owners take it as part of contractual documents to control the contractor's progress, while contractors use it to manage progress and cash flow. Projects often encounter changes and disruptions in the course of construction. If the disruptions and changes occur on the critical path, contractors can easily claim for the time delay and ask for an equitable adjustment for the damage arising thereof. However, if the disruptions and changes are not on the critical path and will not cause project delay, it would be difficult for contractors to claim for price adjustment due to the lack of a baseline for identifying the damages. Traditional network scheduling techniques such as CPM and PERT have introduced two S-curves; one is the early start S-curve and the other late start S-curve, but neither can be considered as a baseline due to their natural limitations. Many previous studies have attempted to find solutions. However, not a single model, which has been established and broadly recognized, is capable of identifying an optimal S-curve from the contractors' perspective. This paper aims to fill this gap.

2. LITERATURE REVIEW

Numerous studies have been made on the construction schedule. Plentiful results are found on areas of; (1) resource allocation, (2) resource leveling, and (3) time-cost trade-off by using various technical, such as linear programming, dynamic programming, expert systems, neural networks, and genetic algorithms.[6], [7], [9], [12], [13], [15]. And some researches used historical data and statistical method to fit or forecast the S-curves, [1-5], [8], [10], [11], [14].

However, the concept of minimizing construction cost, while considering the costs for resources mobilization and demobilization and the trade-off

relationship between different resources, has drown little attention of previous researchers.

3. RESEARCH DESIGN

By using genetic algorithms technique, this research aims to build a model, which can be used to calculate and identify early start, late start, and the contractors' optimal S-curve.

3.1 Assumptions

This research is designed under the following assumptions:

1. Projects are contracted under a fixed duration, which is considered as an optimal duration for executing the project. The issue of Time-cost trade-off is not included in this research.
2. Projects are performed in optimal working sequences based on a fixed duration. The optimization process doesn't change the relationship between activities.
3. There is an ideal resource arrangement for each activity before the optimization process. The workload in each activity will not change during the optimization process.
4. For a specific task, there is a trade-off relationship in terms of work productivity between any two different types of resources.
5. There are unlimited resources available for the projects and the costs of the resources mobilization and demobilization shall be charged to the contractors.

3.2 Genetic Algorithms

Genetic algorithms mimic Darwinian principles of natural selection by creating an environment where hundreds of possible solutions to a problem can compete with one another and only the "fittest" survive. Just as in biological evolution, each solution can pass along its good "genes" through "offspring" solutions so that the entire population of solutions will continue to evolve better solutions.

3.3 Objective Function

Each activity (activity k, k = 1---n) contains several types of tasks (task I, I = 1---n), each tasks need several types of resources (Rj, j = 1---n), each resource consists of several gene cells, and the cell value is designed between 0 and 1. The chromosome for each activity is as shown in figure 1.

	Activity A								.....	Total
	Task1				Type2				.....	Float
Resource type →	R1	R2	R3	.....	R1	R2	R3	.....	.....	.....
Gene value →	r11	r12	r13	.....	r21	r22	r23	.....	.....	tf

Figure 1 Chormosome

In the model, R_j resource is the best suitable for the task i when i=j, but it can be replaced by other resources. The initial gene value rij is 1 when i=j, and rij is 0 when i≠j. While resource trade-off occurs, the gene value will be used to identify the replaceable resource quantity; for example, if R1 is replaced by R2 in the type1 task, resource quantity R2 can be express as below formula (1);

$$R2 = \frac{r12}{r11 + r12 + r13} \times Rl_0 \times \frac{1}{PL} \quad \cdots\cdots\cdots (1)$$

$R1_0$ is the original resource quantity of R1 in the task1, and PL is meant for Productivity loss rate.

The objective function is as equation (2):

$$Min\{TC_g / TC_0\} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

While TC_o is the total cost according to the early schedule plan, TC_g is the total cost after G.A. Optimization.

The optimization process starts from the early schedule and shifts the non-critical activities within the time span of total float.

4. APPLICATION

A project, which includes twenty activities, is used for the study. The durations and workloads of each activity, the unit price of each resource, and working sequences are as shown in Table 1.

The commercial software MS excel and MS project are adopted to analyze the project data and plot s curve. Genetic algorithms software Palisade Evolver is used to perform the optimization process.

4.1 Resource Trade-off

Based on the general chromosome model as describes in figure 1, each activity consists of three tasks and each task needs three types of

resources. Therefore, in addition to the gene cell of the total float, each activity requires 10 genes to form the chromosome.

Table 1 Project Data

Activity	Duration (days)	Precedence	Total Float (days)	Workload (source require to finish the activ		
				R1	R2	R3
A	6		0	60	30	18
B	2		9	26	42	18
C	4	1	0	32	64	64
D	6	3	13	180	144	108
E	8	2	9	128	240	96
F	10	3	0	120	60	90
G	3	4	13	15	6	18
H	2	5	9	20	20	16
I	2	8	9	12	8	16
J	7	6	0	105	210	147
K	1	9	9	10	10	15
L	2	7	13	24	16	16
M	5	11	9	35	35	35
N	2	12	13	14	16	16
O	3	13	9	45	45	36
P	5	10	0	75	50	75
Q	6	15	9	180	240	252
R	2	14	13	20	12	12
S	6	16	0	72	144	216
T	2	17,19,18	0	4	24	8
Total Resource required				1177	1416	1272
PS:Unit price of resources R1=1000,R2=1200/day,R3=1300/day						

The unit prices of resources R1, R2, R3 are 1000, 1200, and 1300 respectively. Different types of resources are assumed replaceable with productivity loss as table2; for example, if R1 is replaced by R2, the productivity will be reduced to 90%. And, the mobilization and demobilization costs are assumed 20% of the resource's unit price. When mobilization and demobilization costs are higher than the resources trade-off costs, the resources trade-off occurs.

4.2 Optimization Process

Since this model is set to focus on the optimization of cost without considering resource leveling, in consideration of the costs of resources and their mobilization and demobilization, the total cost calculated based on the early start schedule and late start schedule are 4,667,280 and 4,688,060 respectively. A near optimal cost, 4,640,540 is further obtained through imputing the total float and the trade off relation between resources. Three S curves, which are plotted based on the early start schedule, the late start schedule, and the optimal schedule, are shown in figure 2. That the optimal S curve positions between the early start S curve and late start S curve means the optimal schedule is reasonably ahead of the late schedule and behind the early schedule at a specific time. Furthermore, according to the comparison of resource utilization between the early start schedule and the optimal schedule in figure 3, the allocation of resources in the optimal schedule is much smoother than that in the early start schedule. It indicates that the cost minimization process simultaneously improve the allocation of resource.

Table 2 Productivity Loss Rate

	R1	R2	R3
R1	1.00	0.90	0.95
R2	0.80	1.00	0.90
R3	0.75	0.85	1.00

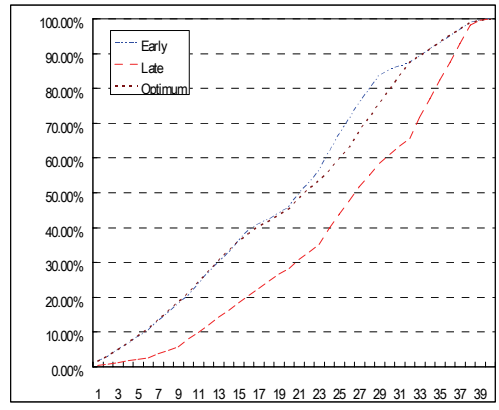


Figure 2 The Optimal S-Curve

5. CONCLUSIONS

Under the reasonable assumptions of the trade off relationships between different types of resources and the resources mobilization and demobilization costs, this research successfully proposes a contractors' S curve model, which can be used to obtain the lowest overall construction cost and identify the near optimal schedule including the optimal quantities for each resources and the timing of performing each activity. Furthermore, this model suggests that any disruptions of works in the course of construction will cause extra costs to contractors and contractors are entitled to claim for an equitable adjustment when the disruptions are not caused by the contractors.

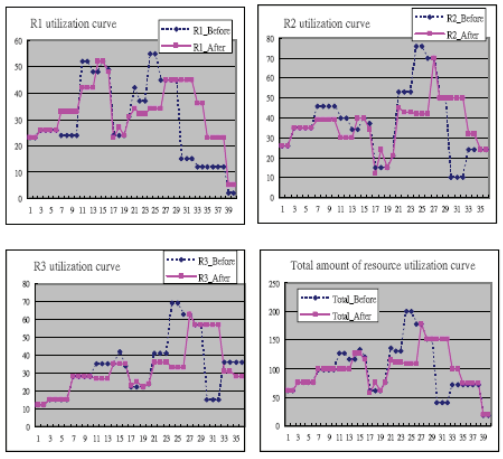


Figure 3 The Resource Leveling

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A MODEL FOR AUTOMATED GENERATION OF RESOURCE-DRIVEN CONSTRUCTION SCHEDULE FOR HOUSING INDUSTRY

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ABSTRACT

The efficacy of managing a construction project mainly depends on proper planning and scheduling. Mass housing projects are highly repetitive in nature, as the methods used for construction are often repetitive or cyclic. Resources are therefore being deployed repeatedly for the similar or identical tasks in these projects. In order to eradicate delays in mobilizing resources, an efficient resource schedule is required. Traditional scheduling tools like Critical Path Method (CPM), Programme Evaluation and Review Technique (PERT) are less effective in scheduling repetitive construction projects, as they consider availability of resources are unlimited. The main challenge in preparing construction schedule for repetitive projects is synchronizing the precedence logic and the allocation of resources as per requirements for all the activities. Consequently, activity scheduling and resource planning are prepared in parallel and this will facilitate in eliminating delays and idle resources across the projects thereby, controls the chain-reaction management (ripple effects). Nevertheless, almost all the repetitive scheduling methods developed so far have been giving focus on continuous repetitive projects, whereas in the present study, the emphasis is on discrete (non-linear) repetitive projects. This paper presents a model that uses genetic algorithms to optimally assign resources to repetitive activities, which aimed to minimize the total project cost & duration, idle cost & time and to maximize resource utilization. In the present study, an attempt is made to generate a resource-driven construction schedule automatically, with which resources can optimally be allocated to the activities. This schedule can be very useful in improving productivity and saving construction time and cost and also in decision-making. In addition, a case study is delineated to check the efficiency and effectiveness of the resource-driven construction schedule which is automated.

KEYWORDS

Resource Scheduling, Optimization, Genetic Algorithm, Repetitive Project

1. INTRODUCTION

Mass housing construction projects are highly repetitive in nature; since they have lots of repetitive activities which involve repetition of a unit throughout the project. This practice is similar to manufacturing assembly lines. However, in repetitive projects, it is labour and equipment that flow through the product (construction site) while in manufacturing assembly lines, it is the product flowing across stationary labour and equipment [1]. In other words, the products are stationary, whereas resources move from location to location and perform the same work. So the resources will be expertise in their tasks and the effect of learning curve will be more. The repetitiveness of these works is based on the activities involved, the

relationships between the activities within a particular unit and the resource required to carry out the tasks. The traditional scheduling methods like bar chart, CPM, PERT focus on the project duration and give little consideration for effective use of resources. However, the site managers and contractors are more concerned about the effective use of resources rather than critical paths or early completion of the project [2]. The main concern is that these techniques do not consider the availability of resources while calculating the completion time of the project. Moreover, these techniques produce large and complex schedules when applied in the repetitive activities and the complexity increases with the increase in repetition. Hence it is highly impractical for projects that give more importance to resources allotment like mass housing projects. Another limitation is its inability to maintain crew work continuity [3]. Therefore, a schedule for smooth movement of resources is needed for minimizing the idle time, thereby maximizing the resource utilization.

1.1. Challenges in Scheduling Housing Projects

The development of an effective plan for scheduling and control of the mass housing construction involves a number of challenging tasks mainly repetitive activities as in our case. On the other hand, repetitive activities have to be scheduled by a technique that can provide resource-driven scheduling. This can be achieved by integrating traditional network scheduling and resource-driven scheduling techniques in an effective environment [4]. To achieve this, an algorithm has to be developed that incorporates utilization of resources. The resource includes both labours and sub-contractors apart from the tools and equipments. The algorithm should also consider the practical aspects that commonly encountered in this kind of projects.

The objective of this study is to develop a scheduling algorithm for repetitive projects that minimize the project duration and maximize the resource utilization. This algorithm should satisfy the three main constraints: i) precedence logic ii) resource availability iii) continuous deployment of resources. It should also consider the impact of a number of practical factors namely, typical activities, crew availability period on site, utilization of crews, activity interruption, sequence of construction operations, impact of weather and learning curve. To deal with this, the algorithm is developed in two phases: the first phase is to select the appropriate resource/crew option to deploy the resources continuously in optimal way thereby maintaining crew work continuity and the second is to prepare the schedule considering the precedence logic and resource/crew availability constraints.

2. KEY FACTORS IN SCHEDULING PROBLEM

To achieve success in a project, resource planning is a key issue. The main factors listed below are internally interlinked with each other in the resource scheduling.

2.1. Repetitive Projects

A repetitive project involves repetition of a unit network throughout the project. The unit network consists of the activities and their relationships that represent the work to be performed in each unit. The resources (labours and equipments) will perform same job in all the units. Hence the quality of the construction and learning curve will be more and also construction work speeds up [5].

2.2. Idleness

Format for A4 size paper (21cm X 29.7cm) It is common that in repetitive projects the resources are idle and waiting because the resources of precedence activity have not finished the jobs (in other words, the resources are not released from the previous activity). The idleness is due to unbalanced production rates and variation during execution. On the other hand, the jobs are pending and waiting for the crew. It is due to the shortage of labours and can be avoided by proper resource planning [6]. Both the resource idle time and the job waiting time are internally controllable and different from the forced causes like bad weather, labour accidents, etc. This results in higher costs and possible delay.

2.3. Continuous Resource Deployment

In the repetitive projects, the same set of resources will perform same kind of jobs. If these resources (labour and equipment) are not properly allocated among all activities, the continuity of work will get affected. Hence the deployment of resources is significant [7]. By planning the resources with continuous deployment, idleness can be reduced.

2.4. Work Continuity

Even if the resources deployed continuously, the job cannot be started because of the work in progress of the preceding activity. So the crew allotted for that particular activity is forced to wait till the space vacated by the crew allocated for the preceding activities [8]. This idle time turns to the excess of project cost. Hence it needs to be minimized to have the project in control. Here, the idleness is due to the varying production rates and the delay is because of the inspection, rework, etc.

2.5. Limited Resource

Because of the limited resources, there is the probability of project getting extended. In order to complete the project in minimum duration, resources have to be managed effectively. In the repetitive project, each unit composed of various repetitive activities which will be performed by different types of resources. Consequently various combinations of available resources are produced and optimized using genetic algorithm to get a schedule of reasonable duration [9].

The findings of this literature review have been effectively used in the development of the proposed model for scheduling repetitive projects. Fig.1. shows the job movement from one activity to other as well as one unit to the other and also shows the resource movement from one place to another in a typical repetitive network.

3. MODEL DEVELOPMENT

The model is designed considering various practical factors commonly encountered in the housing projects. In order to identify these practical factors, a series of discussions were conducted with the site engineers and managers. The findings of these discussions and the literature reviews were considered in the development of the algorithm.

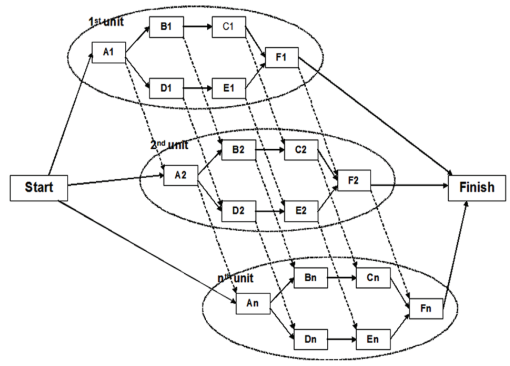


Figure 1 Typical Repetitive Network

A software tool was developed to generate the automated resource-driven schedule. It was intended for getting the information from user, combining genetic algorithm with the schedule. It was developed by integrating Visual Basic, spread sheet and commercial GA based tool for optimization. Fig.2 illustrates the conceptual idea behind the scheduling algorithm.

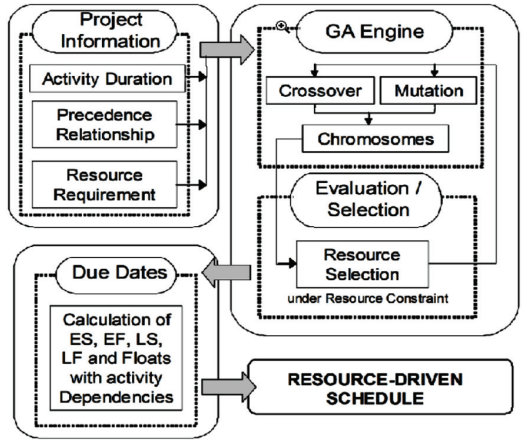


Figure 2 Proposed System of Scheduling with GA

3.1. Model Description

- Variables: Allocation of resources / crew to each of the activity, sequence of the activity according to the resource availability.
- Objective function: To minimize the project duration and maximizes the resource utilization.
- Constraints: a) Precedence logic b)Limitedly

available resources (crew) c)Continuous deployment of resources

- Assumptions: a) The duration is deterministic. b) The availability of materials and equipments are unlimited.c) The activities will be completed in time as per the productivity mentioned. d) No splitting of activity is employed.

3.2. Model Explanation

This research primarily focuses on the planning aspects of housing projects, considering associated constraints like resource availability, precedence logic, and the idle time of resources and the work continuity. The planning process entails

1. Selecting the optimum resource/crew for each of the activity.
2. Developing the schedule for all the activities of all the units in the entire project

The proposed model is designed to automate the schedule according to the precedence logic and resource requirement. The project implementation and the controlling system are outside the scope of this work.

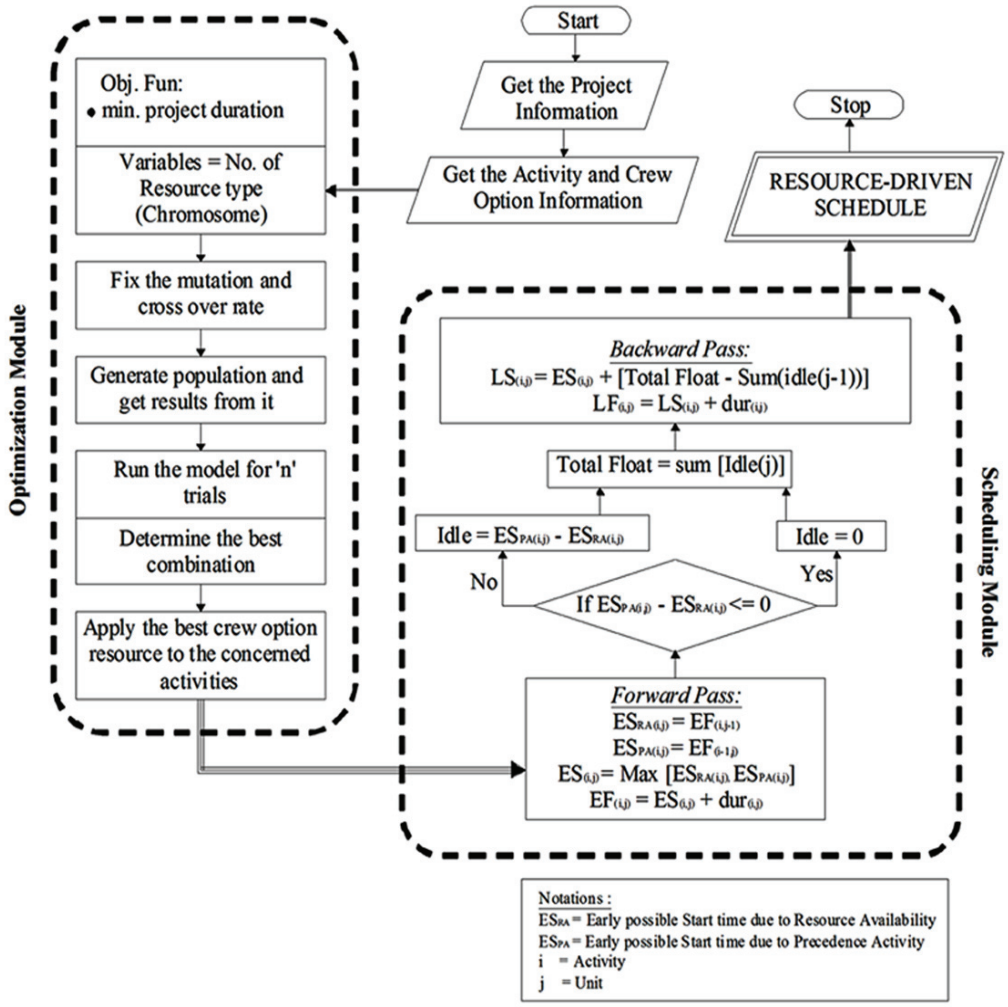


Figure.3 Flowchart of the Scheduling Algorithm

3.2.1 Phase One

The objective of the research is to acquire the appropriate resource/crew combination that minimize the project duration and to select the best crew option for each of the activities. In order to get the best resource/crew combination, the genetic optimization starts with the generation of population (chromosome). The number of chromosome or the population size is the number of the resource/crew type. In the present application, user is given the flexibility to input the mutation and cross over rate. Then, generations are created for the resource/crew combination and checked for the optimal solution. It is to be noted that the crew options are the variables to be optimized in order to get the minimum duration with maximum resource utilization.

3.2.2 Phase Two

In this phase, the schedule is developed by integrating the tasks and the resource availability. The optimum resource/crew option that obtained as output from the phase one is the primary information to control the duration of the each activity. It involves determining the commencement and completion times of each of the activities, work in progress and the resource/crew availabilities and also in allocation of the given resources to various activities in the units. Here the allocation is based on the location of each unit's site in order to avoid wastage of time and cost of mobilizing the resources/crew. The precedence logic among succeeding activities is 'finish to start' and with or without lag time.

4. CASE STUDY

4.1. Description

A Tsunami housing project at Nagapatinam, Tamil Nadu, India is delineated to illustrate the use of the developed resource-driven scheduling model and to demonstrate its capabilities. This project basically a calamity (Tsunami) relief project carrying out by the Government of Tamilnadu associated with other Non Government Organizations. After the Tsunami hit in Dec 2004, there is an immediate need for permanent accommodation for the people in the coastal area since the many of the coastal villages are totally washed away. Here one of the villages is demarcated which consists of 451 houses and construction of each house involves 13 activities. The resource (crew) availability is limited and therefore there is a need for allocating the available resources/crew to each of the activity as per the requirement. The management of the crew is found to be a major problem after regular discussion and meeting with the site and project managers. For the sake of making this paper concise, we have delineated the developed model with a set of fifteen units. The priority of construction is given according to the location of the each unit's site for easy mobilization and sharing of resources. The houses were named in consistent with their position (matrix form) of the entire project site. Each activity is performed by a crew that progresses from the first unit to the last unit sequentially. The precedence logic is 'finish to start' and without lag time. The various crew options are provided with the labour composition and their productivity rate. The concerned input of the housing project is shown in Table 1. The model can be executed even for a project having different types of construction units. It can also comprise of different crew compositions among the resource/crew options.

Table 1 Input Statement of the Housing Construction

S.No	Activity Name	Resource Composition			Resource Option		
		Skilled	Semi skilled	Unskilled	1	2	3
1	Excavation	1	6	5	1	1.5	1.25
2	Foundation	2	8	5	1	1.5	1.25
3	Column	2	7	4	3	3.5	3.25
4	Grade Beam	2	7	3	5	5.5	5.25
5	Brickwork I	6	12	6	5	5.5	5.25
6	Concreting	4	15	6	9	9.5	9.25
7	Curing	0	0	2	9	9.5	9.25
8	Dummy col &Decentering	1	1	1	3	3.5	3.25
9	BrickworkII	8	4	2	3	3.5	3.25
10	Plastering	12	6	3	6	6.5	6.25
11	Flooring	9	6	3	1	1.5	1.25
12	Painting	3	3	2	7	7.5	7.25
13	Finishes	0	0	3	2	2.5	2.25
	Total	50	75	45			

4.2. Validation of the Model

The GA optimization model is executed with the population of 50, mutation rate of 0.1 and the crossover rate of 0.5. The total optimization time taken for simulation is 9.43 minutes and the output is shown in fig.4. It gives the overall detail about the resource used and the time taken for completing each activity as well the project. The detailed graph of resource/crew distribution and the activity timings can also be extracted from the schedule. It also gives us a clear idea about the crew idle time and the job waiting time. So we can mobilize external resources or slow down some of the activities according to the budgeted cost of the project. In short, it also acts as a decision making tool. The auto-generated schedule shows the project duration as 99.5 days. The varying duration in each of the unit denotes the varying productivity of crew options and their availability.

The actual construction on site is in process from October'05 and lagging behind the planned construction schedule as resource planning is not given importance. Hence, this optimization model can be used for further scheduling of resources and activities and for improving the construction. It can be tracked and compared for future research.

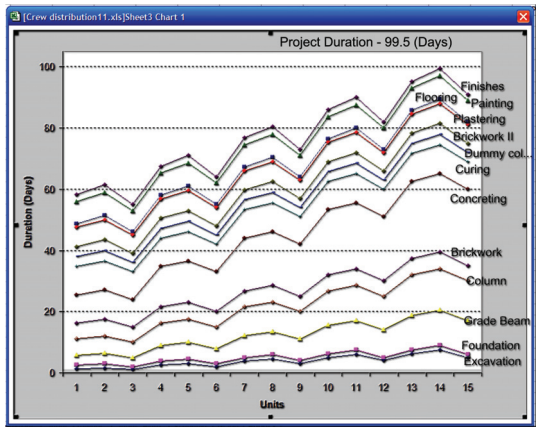


Figure 4 Activity and Resource Schedule of the Housing Construction

The generated resource options are the best crew combination to obtain minimum project duration with maximum crew utilization. External resources can be mobilized for the activities grade beam, column and for concreting to lessen duration. Each unit is completed in varying duration because of the ripple effect.

5. CONCLUSION

The resource-driven scheduling model was developed as a generic model that can be applied to schedule all types of repetitive construction projects such as: housing projects, high-rise buildings, highway construction, pipeline networks and segmental bridge construction. Due to its generic nature, the model considers even the special characteristics and unique requirements if its productivity is defined properly. The model employs resource-driven scheduling, accounts for the impact on crew productivity and considers the beneficial effect of the learning curve. It also facilitates the allocation of resources to activities in process. A case study is delineated to demonstrate the features of the developed model and to illustrate its applicability to planning the mass housing projects.

The proposed algorithm is applied, only for the crew that is being utilized in this project. However it can be expanded to the equipment and materials also. The construction schedule and optimum allocation of resources are the direct output. The priorities, extra mobilization of external resources and the forecasted results are the indirect outputs that help in decision making for the site manager or project manager. This tool can be used by the top management level and can be easily transferred to the low level.

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SIMULATED ANNEALING ALGORITHM FOR OPTIMIZING MULTI-PROJECT LINEAR SCHEDULING WITH MULTIPLE RESOURCE CONSTRAINTS

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ABSTRACT

This paper integrates multi-project scheduling and linear scheduling concepts. Since the problem is combinatorial, a two-stage heuristic solution-finding procedure is used to model the problem with multiple resource constraints. Simulated annealing is utilized as a searching engine in the second stage to find the probable optimized solution. The first stage is slightly different from the other two-stage solution finding procedures which are proposed till now. A numerical example of a multi-project situation is given and solved as well.

KEYWORDS

Linear Scheduling, Multi Projects, Multiple Resource Constraints, Simulated Annealing.

1. INTRODUCTION

Since CPM is not effective for scheduling of linear projects, some other methods like Line of Balance method (LOB) [1], Vertical Production Method (VPM) [2] and Linear Scheduling Method (LSM) [3] have been developed. LSM is utilized in this research. Practically, resources are limited in construction projects so multiple resource constraints are incorporated in the model by" resource leveling" and "resource allocation". Optimizing linear scheduling projects with multiple resource constraints is a combinatorial optimization problem, so it should be optimized by one of the combinatorial optimization tools. Simulated annealing is chosen for achieving this goal in this paper.

LSM was introduced by Johnston in 1981 [3] in a highway construction project. Figure 1 depicts a Linear Scheduling Method diagram. It is a time versus location or distance diagram. Activities are presented as line segments, blocks, or bars in the diagram. The slop of the line segments represents the production rate of the corresponding activities [4]. Harmelink (1995) [5] established a heuristic algorithm to determine the controlling activities path but without consideration of resource limitations. "Controlling activity path" in linear scheduling is a concept similar to "critical path" in CPM. Controlling activity path is a set of activities that constitute a path and dictate project duration. Mattila (1997) [6] considered resource leveling in a model of highway construction project. He solved the model by using mixed integer programming. Liu (1999) [7] considered single resource allocation and proposed a heuristic solution procedure using the Tabu Search algorithm in his model. The model included two stages. Lue & Hwang (2001) [8] proposed a precast production project and solved it with a genetic algorithm-based model.

Simulated annealing is introduced in 1983 in the science magazine [9] in 1983.This concept has been used in several engineering applications since 1983 but it is introduced to construction management by Chung-I Yen (2005) [10]. He proposed simulated annealing for optimizing linear scheduling projects with multiple resource

constraints. He considered resource allocation and resource leveling simultaneously.

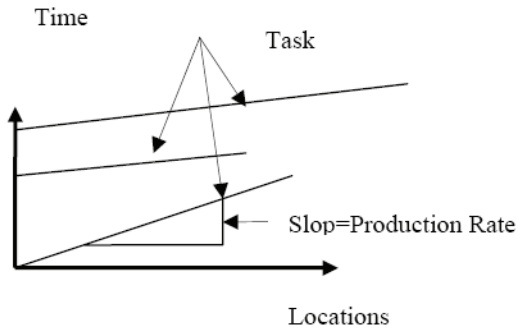


Figure 1 Typical Linear Scheduling Diagram in Highway Construction

2. MULTI PROJECTS

The resource-constrained multi-project problem is defined as one in which two or more projects are concurrently active [11]. There are two approaches for scheduling of multi-project situations i.e. multi-project and single project approach. In the former, projects are considered separately but projects are connected to each other in the latter. The multi-project approach is used in this paper. The first attempt in this field is done by Fendley (1968) and a lot of heuristics are proposed since 1968.

Various projects are not the same and there are unequal delay penalties. The unequal delay penalties arise if the type supervision associated with each project is different, or the delay penalties are assigned by the customers, or if the profit contributions of the projects are different [11]. Since projects are different, a weighting factor is defined for each project to be able to produce objective functions in the formulation stage. The weighted factor can be calculated based on the delay penalties.

3. SIMULATED ANNEALING ALGORITHM

Simulated annealing is based on the similarity between solid annealing process and combinatorial optimization. The algorithm consists of several decreasing temperatures.

Suppose that finding the minimum of the cost function is favorable. Each temperature includes a sequence of iterations. First, the beginning temperature is chosen and the initial solution is selected and the cost function will be calculated. Then a new solution will be created in the neighborhood of the previous solution. New cost function will be calculated. If new cost function is less than the previous one, it will be accepted. If new cost function is less than the previous one, it will be accepted according to Metropolis's criterion [Metropolis et al., 1953] based on Boltzman's probability. According to Metropolis's criterion, if the difference between the cost function values of the current and the newly produced solutions (ΔE) is equal to or larger than zero, a random number δ in [0,1] is generated from a uniform distribution and if

$$\delta \le e^{(-\Delta E/T)} \tag{1}$$

Then the newly produced solution is accepted as the current solution. The number of new solutions which are created in each temperature is as many as the iteration number (termination condition). Iteration number can be a certain number of moves [10]. Then temperature will reduce upon temperature update rule and every above-said step will be iterated until the temperature goes down the minimum temperature (halting criteria) [9]. The result will be affected with the number of iterations and the speed of reducing temperature. The halting criterion in this research is equation (2).

$$Temperature = Te^{(-rt)} \tag{2}$$

Where T is the initial temperature, r is a cooling ratio, and t is the number of times that temperature has been used. The chosen r is 0.1 in this research.

4. PROBLEM FORMULATION

Assume there are two linear projects with $N_1 + N_2$ activities, M locations, and I critical resources. n represents an activity i.e. one of ($N_1 + N_2$) activities but n_1 and n_2 represents activities of the first and second project respectively. The final program is based on this formulation. These formulas are based on those formulas which are proposed for a single linear project scheduling [10]. The problem is formulated as follows:

Objectives:

$$Minimize Max \quad \{w_1 f(n_1,m)+w_2 f(n_2,m) \mid n_1=1..N_1; n_2=N_1+1..N_1+N_2; m=1..M\} \quad (3)$$

$$Minimize \sum_{t=1}^{T-1}\sum_{i=1}^{I} W_i(dp_{t,i}+dm_{t,i}) \text{ [10]} \quad (4)$$

Constraints:

- Activities precedence relationships

$$s(n_1,m+1) \geq f(n_1,m)$$
$$\forall n_1 = 1, N_1; \forall m = 1, M \quad (5)$$

$$s(n_2,m+1) \geq f(n_2,m)$$
$$\forall n_2 = N_1+1, N_1+N_2; \forall m = 1, M \quad (6)$$

$$s(1,1) \geq \alpha \quad (7)$$

$$s(N_1+1,1) \geq \beta \quad (8)$$

$$s(n_1,m) \geq f(p_1,m) + L(n_1,p_1)$$
$$\forall m = 1...M; \forall p_1 \in P_1(FS) \quad (9)$$

$$s(n_2,m) \geq f(p_2,m) + L(n_2,p_2)$$
$$\forall m = 1...M; \forall p_2 \in P_2(FS) \quad (10)$$

$$s(n_1,m) \geq s(p_1,m) + L(n_1,p_1)$$
$$\forall m = 1...M; \forall p_1 \in P_1(SS) \quad (11)$$

$$s(n_2,m) \geq s(p_2,m) + L(n_2,p_2)$$
$$\forall m = 1...M; \forall p_2 \in P_2(SS) \quad (12)$$

$$f(n_1,m) \geq s(p_1,m) + L(n_1,p_1)$$
$$\forall m = 1...M; \forall p_1 \in P_1(SF) \quad (13)$$

$$f(n_2,m) \geq s(p_2,m) + L(n_2,p_2)$$
$$\forall m = 1...M; \forall p_2 \in P_2(SF) \quad (14)$$

$$f(n_1,m) \geq f(p_1,m) + L(n_1,p_1)$$
$$\forall m = 1...M; \forall p_1 \in P_1(FF) \quad (15)$$

$$f(n_2,m) \geq f(p_2,m) + L(n_2,p_2)$$
$$\forall m = 1...M; \forall p_2 \in P_2(FF) \quad (16)$$

- Resource availability

$$\sum_{m=1}^{M}\sum_{n=1}^{N_1+N_2} r_i(n,m,t) \leq RA_i(t)$$
$$\forall t = 1, T; \forall i = 1, I \quad (17)$$

- Activities completion

$$\sum_{t=1}^{T} r_i(n,m,t) \geq TR_i(n,m)$$
$$\forall n = 1, N_1+N_2; m = 1, M; i = 1, I \quad (18)$$

$$\sum_{n=1}^{N_1+N_2}\sum_{m=1}^{M}[r_i(n,m,t+1) - r_i(n,m,t)] - dp_{t,i} + dm_{t,i} = 0$$
$$\forall t = 1, T-1; i = 1, I \quad (19)$$

Notations:

$s(n_i,m_i)$: Start time of activity n at location m in the first project

$f(n_i,m_i)$: Finish time of activity n at location m in the second project

$dp_{t,i}$: Absolute difference plus value of resource I assignment between day t+1 and day t

$dm_{t,i}$: Absolute difference minus value of resource I assignment between day t+1 and day t

W_i: Weighting factor for resource i

w_i: Weighting factor of various projects

$r_i(n,m,t)$: Resource i assigned to activity n at location m at time t

$RA_i(t)$: Resource i availability at time t

$TR_i(n,m)$: Total amount of resource i required to complete activity n at location m

α: Start time of the first project

β : Start time of the second project

$L(n, p)$: The lead time between activity n and its predecessor p

p : Set of all predecessors of activity n.

5. SOLUTION METHODOLOGY

A two-stage solution-finding procedure is introduced in this section. These two stages are explained briefly. In the first stage a simple feasible solution for each project is proposed. In this method we imagine that activities don't have any overlapping in each project so the first activity of each project in all locations is finished before the second activity of that with the second priority starts and it continues till each project is finished. In the other words, it is the maximum duration for each project but it guarantees that we have enough resources for activities to be done. It is assumed that resources are fixed for an activity in all locations in this stage.

Simulated annealing is used during the second stage to find the optimized solution. The number of one of the resources of one of the activities is changed in each iteration of the algorithm to find the best allocation. The problem will be solved by multiple-resource allocation algorithm. NTF concept is utilized in solving by considering multiple resource constraint. The resources assigned to a repetitive activity can be varied at different locations within a specified range. The goal is to find best assignment of resources to activities to have the minimum sum of weighted project durations and fluctuation of resources assigned for the projects. So search neighborhood is all possible resource assignments to activities. The maximum and minimum temperatures are 1000 and 1 respectively.

6. NUMERICAL EXAMPLE

In this section two projects are introduced as a multi-project problem to be solved by the model which is proposed. The following assumptions have been observed [3]:

1. A task can not be split. Once an activity is started, it will continue without interruption until it is finished.
2. Resources are limited. The limitation is assumed to be a constant across the entire project life span.
3. A resource con not be split, i.e., the resource amount is a positive integer.
4. Resources are assumed to maintain a constant productivity level within a certain range of assignment.
5. A resource can not be split.

Table 1 lists required information about the proposed artificial projects and their activities. Project 1 consists of activities A to E and project 2 consists of activities F to K. Table 2 presents information about resources. It is assumed that resources are labors. The maximum number of Labor 1 and 2 are 8 and 6 respectively.

Table 1-Required Information About Activities

Activity	Duration (Days)	Predecessor
A	4	
B	2	A (FS0)
C	2	B(FS0)
D	2	C(FS1)
E	1	D(FS0)
F	3	
G	2	F (FS0)
H	4	G (FS1)
I	3	H (FS0)
J	1	I (FS0)
K	4	J(FS2)

The goal of this problem is to find the best resource assignment combination and the best sequence of activities to minimize the sum of weighted project durations and the fluctuation of resource usage. The main objective is to find the minimum of the sum and the second objective (minimum fluctuation of resource usage) is used when there are two schedules with the same sum. α and β are both 0 in this problem.

Table 2 Required Information About Resources

Act.	L1	L2	Total L1 Required	Total L2 Required	Activity priority	L1 Range	L2 Range
A	3	2	4*3=12	4*2=8	1	2-4	1-3
B	2	1	2*2=4	2*1=2	2	1-3	1-2
C	2	1	2*2=4	2*1=2	3	1-3	1-3
D	1	1	2*1=2	2*1=2	4	1-2	1-2
E	1	1	1*1=1	1*1=1	5	1-2	1-2
F	2	1	3*2=6	3*1=3	1	1-3	1-2
G	1	2	2*1=2	2*2=4	2	1-2	2-4
H	3	1	4*3=12	4*1=4	3	2-4	1-3
I	1	1	3*1=3	3*1=3	4	1-2	1-2
J	1	2	1*1=1	1*2=2	5	1-2	1-3
K	2	1	4*2=8	4*1=4	6	2-4	1-3

7. RESULTS AND CONCLUSION

The problem is written in Java programming language. The program is run 100 times. The average and the most optimized answer and other information which is achieved from 100 implementations are represented in table3. Table 4 shows the result of scheduling for some activities of the most optimized answer.

The following conclusions can be achieved from the results which are prepared.

- A large number of companies which are related to linear projects manage several projects simultaneously so these two concepts should be integrated in a single model.
- Multi-project and Linear scheduling with multiple resources can be integrated and solved simultaneously. This paper proposes a model to solve this problem.
- There are two approaches for scheduling of multi-project situations i.e. multi-project and single project approach. The multi-project approach is used in this paper.
- The model is verified by a successful numerical example. The summary of implementations is summarized in two tables.

Table 3Results of Implementations

No. of runs	Most Optimized answer	Average	Variance
100	55	68.93	54.93

Table 4 Result of Scheduling for Some Activities of the Most Optimized Answer

Act.	Time	L1 Assigned	L2 Assigned
A1	0-4	3	2
A2	4-8	3	2
A3	8-12	3	2
G1	3-5	1	2
G2	12-14	1	2
G3	14-16	1	2

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AXIOMATIC-DESIGN SCHEDULING METHOD FOR FAST-TRACK CONSTRUCTION

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ABSTRACT

The fast-tracking delivery method has received considerable attention over the last decade because of its time saving feature depending on overlapping of phases of a project. However, to implement the fast-tracking construction, not only the overlapping relationship between design and construction phases, but also the estimating the reduction of the construction duration is difficult to determine. Therefore, this study applies the Axiomatic Design (AD) approach to develop a fast-track scheduling method for design-build project to decompose a project into work packages and further to determine the overlap relationships between work packages. Consequently, based on the determined overlap relationships, the fast-track schedule can be subsequently constructed finally.

KEYWORDS

Fast-Track Construction, Design-Build, Overlap, Project Scheduling, Axiomatic Design (AD)

1. INTRODUCTION

Under a rapidly changing business environment, the fast-tracking delivery method has received considerable attention over the last decade because of its time saving feature depending on overlapping of phases of a project. Therefore, D/B is considered to be the fastest project delivery system as it encourages fast-tracking of design and construction phases. However, to implement the fast-tracking construction, not only the overlapping relationship between design and construction phases is difficult to determine, but the conditions of the resource allocation are also complex to evaluate. Thus, the schedule plan of the fast-tracking construction can not be done easily for most D/B project managers. Meanwhile, due to the difficulty in estimating the reduction of the construction duration, the feasibility and the usability of the fast-tracking construction is decreased. Therefore, the purpose of this study is developing a fast-tracking scheduling method for project managers to construct a fast-tracking network for a D/B project.

Few papers related to the fast-track construction scheduling were addressed. Peña-Mora and Li [1]combined axiomatic design, concurrent engineer, the graphical evaluation and review technique, and system dynamics to propose a dynamic planning and control methodology (DPM) for discovering the potential problems of fast-tracking projects. Moreover, Maheswari and Varghese [2] utilized the dependency structure matrix (DSM) to estimate the natural overlap project duration. The communication time was a new concept addressed in the Maheswari and

Varghese's paper while estimating the normal project duration. Generally, these papers aimed at estimating overlap degrees of two activities to be a reference for creating a construction schedule. Differing from these papers, this study tried to decompose a D/B project into work packages including a couple of design and construction jobs; therefore, the overlap between work packages could be a new concept to reduce the projection duration. To this target, the Axiomatic Design (AD) methodology was applied in this paper.

Axiomatic design provides a framework for describing design objects that are consistent for all types of design problems and at all levels of detail. Thus, different designers can quickly understand the relationships between the intended functions of an object and the means by which they are achieved. Since its first introduction, AD has been successfully applied to computer applications [3][4], manufacturing [5], structural design [6], decision support systems [7], and other areas. By using the axiomatic design methodology, a D/B project can be decomposed to be several design-build packages which respectively consist of a specific pair of design and construction activities, and the overlapping relationships among all design-build packages can be revealed according to the dependence matrices. Once the overlapping relationships of design and construction activities were determined, not only the fast-tracking network can be subsequently generated, but the project duration can also be calculated to evaluate the time benefit of the fast-track construction.

2. AXIOMATIC DESIGN APPROACH FOR OVERLAP ANALYSIS

Based on the AD methodology, this study maps a D/B project into customer, functional, physical and process domains by zigzagging decomposition and creating dependency matrices. Figure 1 shows AD mapping relationships. Each associated domain consists of specific characteristic vectors such as customer need {CN}, functional requirement {FR}, design proposal {DP} and construction activity {CA}.

Concurrently, the design matrix [A] between {FR} and {DP} vectors and the construction matrix [B] between {DP} and {CA} vectors can be evaluated to present the dependences of DPs and CAs. The process of mapping between FRs and DPs allows the dependency relationships between FRs to be expressed mathematically in terms of characteristic vectors defining the functional contribution value of DPs to each FR. The relationship between {FR} and {DP} can be written as:

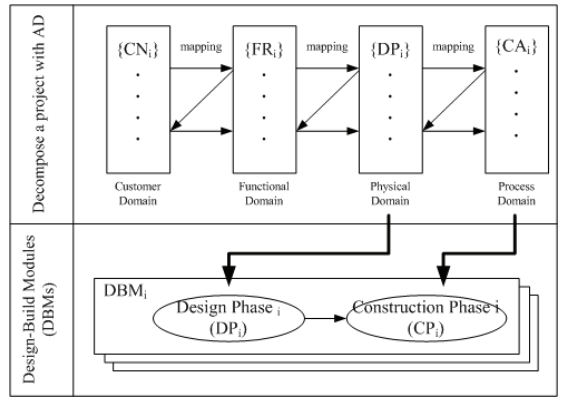


Figure 1 Relation Between the AD Method and Design-Build Package (DBP)

$$\{FR\}=[A]\{DP\} \quad (1)$$

In Equation (1), [A] expresses the functional contribution values of design proposals to each FR. After referencing the contribution relationships within this matrix [A], dependency relationships between FRs can be determined by clustering their related DPs. Similarly, Equation (2) shows the mathematical relationship of {DP} and {CA}. The matrix [B] is defined as a construction matrix representing the dependent relationship between DPs and CAs concurrency.

$$\{DP\}=[B]\{CA\} \quad (2)$$

Meanwhile, to reduce the complexity raised by overlapping between design and construction activities, the relationship between FRs must satisfy the Independence Axiom. That is, the design matrix [A] must either be a diagonal or triangular matrix (as shown in Figure 2(2) and 2(3)). Therefore, by utilizing the AD methodology, engineers can determine the sequence of DPs and CAs in accordance with the matrix type of the matrix [A] and [B].

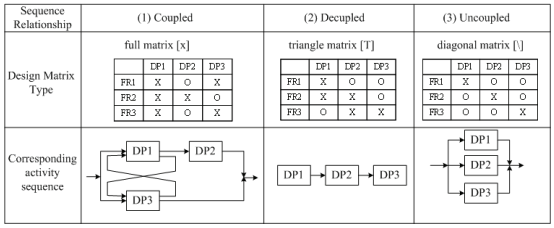


Figure 2 Three Types of Design Matrices of Axiomatic Design Method (Peña-Mora and Li 2001)

Further, to make fast-track possible, this study packages a DP and its corresponding CA into a design-build package(i) (DBPi) as shown in Figure 1, so that dependency relationships among DBPs can be determined based on matrices [A] and [B]. To this aim, the concurrent matrix [C] is applied to summarize the overlapping relationships of DPs and CAs. As Equation (3) shows, matrix [C] is the cross product of matrix [A] and [B].

$$[C]=[A][B]; C_{ik}=\sum_{j} A_{ij}B_{jk} \tag{3}$$

where $C_{ik} \in [C]$, $A_{ij} \in [A]$, and $B_{jk} \in [B]$.

Accordingly, a mathematical relationship, as shown in Equation 4 exists between FR, DP, CA, and DBP.

$$DBM_i=\frac{FR_i}{CPV_i}=\sum_k C_{ik}\frac{CPV_k}{CPV_i}=\sum_j\sum_k A_{ij}B_{jk}\frac{CPV_k}{CPV_i}=\sum_j\sum_k \frac{\partial FR_i}{\partial DP_j}\frac{\partial DP_j}{\partial CPV_k}\frac{CPV_k}{CPV_i} \tag{4}$$

As illustrated in Equation (4), DBP represents the interrelationships between all CA_i through the C_{ik} term. Also, due to the combination of interrelationships between DPs and CAs in the C_{ik}, a DBPi combines not only the direct incremental relationship between FR_i and CA_i , but also the interrelationships among DP_i, CA_i and CA_k. Meanwhile, to reduce the complexity raised by the overlapping of DBPs, no overlap between the DP and CA in the same DBP is encouraged. Table 1 illustrates the dependent relationships between DBP_i and DBP_k.

Consequently, a project can be decomposed to be DBPs which include their specific design and construction works, and the overlapping relationships between DBPs can determined simultaneously.

Table 1 Overlap Relationships Between Two Design-Build Packages (Cheng and Tsai 2005)

Type (Sequence symbol)	Matrix type [A]	[B]	[C]	Overlap Relationship	Description
1 (PP)	[\]	[\]	[\]	DBM$_i$: Design$_i$ → Construction$_i$; DBM$_k$: Design$_k$ → Construction$_k$	Parallel Design & Parallel Construction:
2 (PC)	[\]	[LT]	[LT]	DBM$_i$: Design$_i$ → Construction$_i$; DBM$_k$: Design$_k$ → Construction$_k$	Parallel Design & Continuous Construction :
3 (CP)	[LT] or [UT]	[\]	[LT] Or [UT]	DBM$_i$: Design$_i$ → Construction$_i$; DBM$_k$: Design$_k$ → Construction$_k$	Continuous Design & Parallel Construction :
4 (CC)	[LT] or [UT]	[LT] or [UT]	[LT] or [UT]	DBM$_i$: Design$_i$ → Construction$_i$; DBM$_k$: Design$_k$ → Construction$_k$	Continuous Design & Continuous Construction :
5 (PF)	[\]	[X]	[X]	DBM$_i$: Design$_i$ → Construction$_i$; DBM$_k$: Design$_k$ → Construction$_k$	Parallel Design & Feedback Construction:
6 (CC_b)	[LT] or [UT]	[UT] or [LT]	[X]	DBM$_1$: Design$_1$ → Construction; DBM$_2$: Design$_2$ → Construction$_2$	Continuous Design & Backward Continuous Construction :
7 (CF)	[LT] or [UT]	[X]	[X]	DBM$_i$: Design$_i$ → Construction$_i$; DBM$_k$: Design$_k$ → Construction$_k$	Continuous Design & Feedback Construction :

Denotation: [\] diagonal matrix, [LT] lower triangular matrix, [UT] upper triangular matrix, [X] full matrix.

3. AXIOMATIC DESIGN SCHEDULING METHOD

Combining the AD overlapping analysis approach and network scheduling method, a proposed scheduling method for fast-track construction is illustrated as Figure 3 shows.

3.1 Design Activities Analysis

In this phase, the necessary DPs of a D/B project needs to be derived previously from the owner's needs; subsequently, the design sequence of DPs can be analyzed in accordance with the DPs' design matrix [A] which represents the independence relationships between all DPs. Tis study applied the zigzagging decomposition procedure as shown in Figure 4 to create FRs and DPs hierarchies.

After the FRs in the current level are generated, their corresponding DPs can be determined, and the design matrix corresponding to this level can be evaluated to ensure the DPs within the current level satisfy the Independence Axiom. Table 2

shows the design matrix of FR21 and DP21 which is a lower triangle matrix.

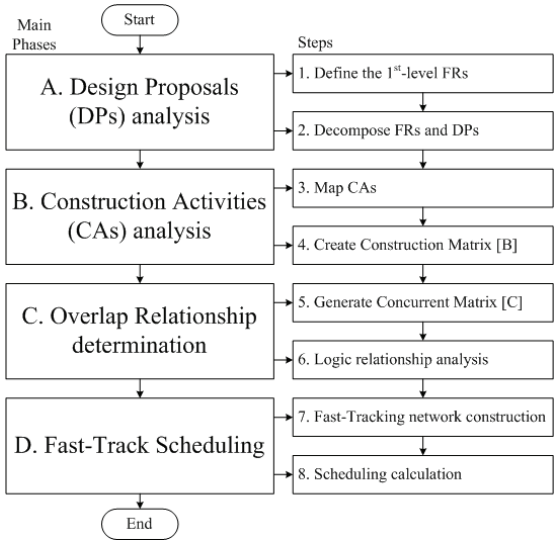


Figure 3 Procedure of the Axiomatic Design Scheduling Method

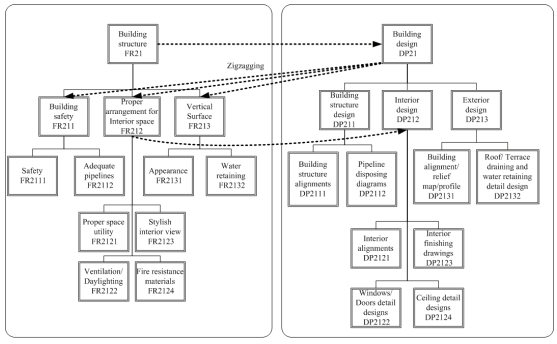


Figure 4 Zigzag Decomposition Between FR21 and DP21 within the Case Study

Table 2 Design Matrix [A] (derived from Fig. 4)

Functional Requirements (FRs) \ Design Proposals (DPs)		Building structure alignments	Pipeline disposing diagrams	Interior alignments	Windows/ Doors detail designs	Interior finishing drawings	Ceiling detail designs	Building alignment/ relief map/profile	Roof/ Terrace draining and water retaining detail design
		DP211		DP212				DP213	
		DP2111	DP2112	DP2121	DP2122	DP2123	DP2124	DP2131	DP2132
FR21	Safety FR2111	X	0	0	0	0	0	0	0
	Adequate pipelines FR2112	X	X	0	0	0	0	0	0
FR2112	Proper space utility FR2121	X	0	X	0	0	0	0	0
	Ventilation/ Daylighting FR2122	X	0	X	X	0	0	0	0
	Stylish interior view FR2123	X	0	X	0	X	0	0	0
	Fire resistance materials FR2124	X	0	X	0	X	X	0	0
FR2113	Appearance FR2131	X	0	0	X	0	0	X	0
	Water retaining FR2132	X	0	0	0	0	0	0	X

3.2 Construction Activities (CAs) Analysis

After the DPs hierarchy is created, the CAs corresponding to DPs and the construction matrix [B] need to determined. Unlike the zigzagging decomposition between FRs and DPs, only direct mapping from DPs to CAs is done in this step. Figure 5 shows the hierarchy of CA21 mapped from the DP21 hierarchy in Figure 4. Table 3 shows the construction matrix of DP21 and CA21.

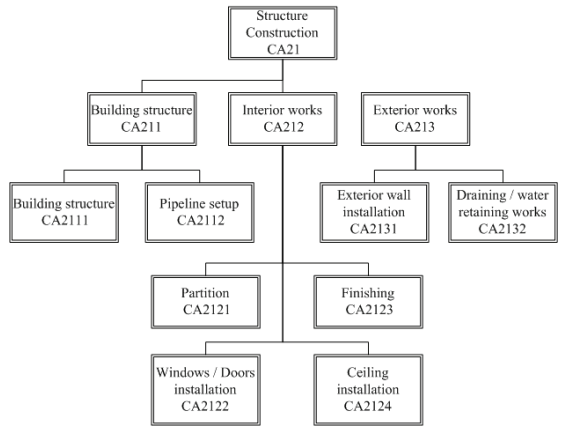


Figure 5 CA21 Hierarchy of Case Study

Once the CAs' hierarchy was created, the matrix [B] can then be generated as Table 3 shows.

Table 3 Construction Matrix [B] of CA21 of the Case Study

Design Proposals (DPs) \ Construction Activities (CAs)		Building structure	Pipeline setup	Partition	Windows / Doors installation	Finishing	Ceiling installation	Exterior wall installation	Draining / water retaining works
		CA2111	CA2112	CA2121	CA2122	CA2123	CA2124	CA2131	CA2132
DP211	Building structure alignments DP2111	X	X	0	0	0	0	0	0
	Pipeline disposing diagrams DP2112	X	X	0	0	0	0	0	0
DP212	Interior alignments DP2121	X	0	X	0	0	0	0	0
	Windows/ Doors detail designs DP2122	X	0	X	X	0	0	0	0
	Interior finishing drawings DP2123	X	0	0	0	X	0	0	0
	Ceiling detail designs DP2124	X	0	0	0	X	X	0	0
DP213	Building alignment/ relief map/profile DP2131	X	0	0	0	0	0	X	0
	Roof/ Terrace draining and water retaining detail design DP2132	X	0	0	0	0	0	X	X

3.3 Overlap Relationship Determination

The primary target of this phase is to determine the overlapping relationships between each DBPs so that the fast-tracking network can be created in the next phase. Two activities should be done in this phase, namely (1) generate concurrent matrix [C],

and (2) logic relationship analysis. First, schedule analysts can do the matrix multiplication of [A] and [B] matrices to generate the concurrent matrix [C], and subsequently, the logic overlapping relationships between each two DBPs can be determined by referring to the matrix type of [A], [B], and [C]. Table 4 shows the multiplication of design and construction matrixes respectively in Table 2 and Table 3.

Table 4 Concurrent Matrix [C] of Case Study

Functional Requirements (FRs) \ Design-Build Packages (DBPs)		DBP211		DBP212				DBP213	
		DBP2111	DBP2112	DBP2121	DBP2122	DBP2123	DBP2124	DBP2131	DBP2132
FR211	Safety FR2111	X	X	0	0	0	0	0	0
	Adequate pipelines FR2112	X	X	0	0	0	0	0	0
FR212	Proper space utility FR2121	X	0	X	0	0	0	0	0
	Ventilation/ Daylighting FR2122	X	0	X	X	0	0	0	0
	Stylish interior view FR2123	X	0	X	0	X	0	0	0
	Fire resistance materials FR2124	X	0	X	0	X	X	0	0
FR213	Appearance FR2131	X	0	0	X	0	0	X	0
	Water retaining FR2132	X	0	0	0	0	0	X	X

After the current matrix has been generated, the logic relationship between two DBPs can be determined in accordance with the relatedness within the matrix [C].

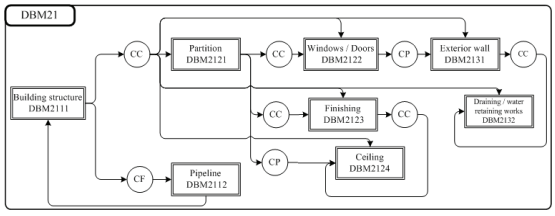


Figure 6 Fast-Tracking Diagram of Case Study

Take FR211 and FR212 in the Table 4 as an example (Black in the Table 4). FR211 and FR212 are both achieved by DBP211 and DBP212 ("full matrix" type). Furthermore, because the matrix [A] and [B] of DBP211 and DBP212 respectively in Table 2 and 3 are lower triangle matrix [LT] and full matrix [X], the overlap relationship between DBP211 and DBP212 is determined as the "*Continuous Design & Feedback Construction"* (CF) as shown in Table 1. In the same manner, all relationships between other DBPs can be determined. Consequently, a fast-tracking diagram as shown in Figure 6 can be generated.

3.4 Fast-Tracking Network Calculation

According to the created fast-tracking diagram, the scheduling network can be schemed out for estimating the overlap project duration. Referred to the overlap relationships in Table 1, predecessors of each design and construction activities can be determined based on the created fast-tracking diagram. Table 5 shows an example of information predecessors and durations of activities for network calculation derived from Figure 6.

Table 5 Predecessors and Durations of DPs and CAs within the Case Study

S. No.	Activity ID	Predecessors	Duration (days)
1	DP2111	-	30
2	CA2111	DP2111,DP2112	160
3	DP2112	DP2111	20
4	CA2112	DP2111,DP2112	80
5	DP2121	DP2111	10
6	CA2121	DP2121,CA2111	80
7	DP2122	DP2121	5
8	CA2122	DP2122,,CA2111,CA2121	40
9	DP2123	DP2121	5
10	CA2123	DP2123,CA2111,CA2121	64
11	DP2124	DP2121,DP2123	5
12	CA2124	DP2124,,CA2111,CA2123	64
13	DP2131	DP2122	15
14	CA2131	DP2131,CA2111	30
15	DP2132	DP2131	10
16	CA2132	DP2132,,CA2111,CA2131	20

Consequently, schedule planners can construct the project schedule as shown in Figure 7. The total duration of the DPs and CAs related to the DBP21 was schemed as 418 days.

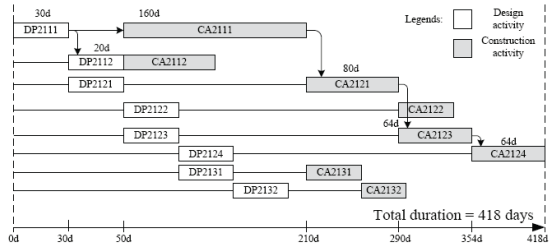


Figure 7 Duration Estimation of Fast-Tracking of Case Study

4. DISCUSSION

Te schedule planners can determine the shorten duration due to the overlaps of DBPs. Taking the case in Figure 7 as an example, the shorten duration of the fast-track construction can be

calculated by comparing with the normal project duration as Figure 8 shows. Accordingly, the shorten duration caused by overlaps was determined as 438- 418 = 20 days.

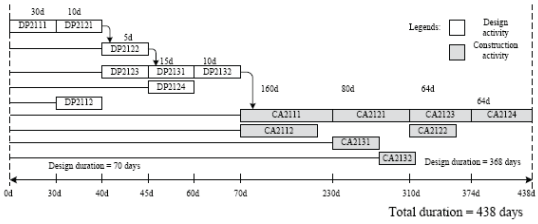


Figure 8 Estimation of Normal Project Duration

Although AD is a powerful method for determining the dependency relationships of design and construction jobs, the situations of resource trade-off were difficult to be considered due to increasing complexity of analysis, especially for the crew resource trade-off of design jobs. Hence, the created fast-tracking diagram presents a sequence plan but resource allocations. To overcome this situation, a resource allocation mechanism for the AD scheduling method is necessary in the future work to enhance the reality of the scheduling result. Accordingly, the advanced improvement for this method is proceeding, and applying to a case study of high-tech factory construction project for validate the feasibility of this concept.

5. SUMMARY

This study proposed a method to create a fast-tracking project schedule including design and construction activities. Based on the created method, a D/B project can be divided into DBPs by zigzagging decomposition between customer needs (CNs), function requirements (FRs), design phases (DPs) and construction activities (CAs). Meanwhile, the overlapping relationships between DBPs can be also identified in accordance with sequence information within the design matrix [A], construction matrix [B] and concurrent matrix [C]. Thus, a fast-tracking network model can be created by summarizing the DBPs and overlapping relationships. Therefore, the shorten duration raised by the fast-track construction can be evaluated by comparing with the traditional linear design and construction method. Based on the scheduling result, planners can not only realize the dependency relationships between design and construction activities, but also evaluate the time benefit of the fast-tracking delivery method for a D/B project.

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MODELING DESIGN ITERATION USING DSM AND SIMULATION

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ABSTRACT

DSM (Design/Dependency Structure Matrix) is a potential tool for planning iterations and also for evaluating alternate sequences. The standard DSM operations can determine the basic sequence and can identify the existence of cycles/loops. These cycles/loops are grouped as blocks. There can be many strategies for executing the activities within the block. The strategy proposed in the present study is 'speed' of execution/iteration. It happens when an activity waits for information from all its predecessors or when it proceeds as soon as new information arrives from any one of its predecessor. The choice on the 'speed' is decided based on the (a) estimation of duration and (b) number of repetition of the activities. Stroboscope, a Monte Carlo simulation engine is attempted to model the proposed strategy. The scope of the present study is limited to time aspects alone and the concepts are elaborated with an example.

KEYWORDS

DSM, Simulation, Basic Sequence, Execution Sequence, Blocks

1. INTRODUCTION

The execution phase of a construction project accounts for a major portion of the project cost and hence most of the planning and management efforts were focused on this phase [1]. However, the decisions made during the design phase have a greater impact on the schedule of the project. This design phase is a process of information exchange among various design domains and is generally iterative in nature [2], [3], [4]. Hence, planning for the design phase is critical.

The basic requirements for design planning include representation of the activities and dependency relationships among the activities. The information dependency between the activities is of three types – independent, dependent, and interdependent or loops [2]. The presence of cycles/loops requires that an assumption has to be made to start/proceed. When the activities start to execute with these assumptions, it is likely that these assumed information might change. Any changes made in the initial assumptions will prompt the succeeding activities to repeat until the desired criterion is met. This periodic repetition of the cyclic activities is termed as iteration [2], [4].

Conventional tools like CPM (Critical Path Method) or PERT (Program Evaluation and Review Technique) are not suitable for sequence analysis because they cannot model iteration [5]. Although advanced graph-based techniques such as GERT (Graphical Evaluation and Review Technique), IDEF (Integration Definition or ICAM Definition), Petri Nets, etc. can represent feedback loops, they are practically limited by the size of the project [6], [7]. Moreover, they cannot explicitly/ distinctly model iterations [6], [7].

Researchers have investigated DSM (Design/Dependency Structure Matrix) as a potential tool to model iterations and to evaluate the resulting sequence [2], [3], [8]. The basic DSM operations such as partitioning and tearing enable the planners to identify the overall sequence along with determination of cycles/loops. This sequence is referred as basic sequence and these cycles/loops if grouped together are denoted as blocks [9].

For a given block, there can be multiple strategies for execution. The available iteration models do not allow any variation in the strategy for executing the basic sequence [2], [4], [9]. In the present study, a strategy of execution based on "Speed" of iteration is defined. "Speed" is based on whether an activity waits for new information from all predecessors before repeating or repeats as soon as new information arrives from any predecessor. For a given block it is not apparent which strategy will result in a shorter duration. The duration depends on the iterative relationships and its dependency attributes. As there are multiple cyclic relationships and probabilistic attributes in a block, models for estimating the duration is not simple.

The objective of this work is to develop a simulation-based model to estimate the duration for a specified execution strategy. To address this objective, Monte Carlo Simulation is investigated. The results of the Stroboscope model are analyzed and discussed. This paper also illustrates the application of the above concept using an example.

2. PAST WORK

The existing iteration models based on DSM are elaborated in this section. Gaps identified from the literature review follows the model types.

The iteration models applied to construction industry treat iteration as a black-box and follow CPM/PERT type scheduling approaches [10], [11], [12]. In Taiwan, researchers have used Stroboscope for modelling iterations in construction projects [13]. They estimate the project duration for no iteration and one-time iteration. Still, 'true' iterations are not modelled for construction applications.

The analytical models cited in the literature such as parallel iteration model and sequential iteration model were applied initially in manufacturing applications [14], [15]. As the real world system is more complex, these models required more assumptions. Browning & Eppinger [16] developed the first DSM-based simulation model that analyzes design iterations with more generalizations than the previous analytical models. The work policy which governs the successive execution assumes that all activities have to wait for all the information to arrive before starting the next activity. The model fails to account for the number of times iteration occurs.

In general, the applications cited above do not allow any variation in the strategy for executing the basic sequence. As stated earlier, there can be multiple strategies for executing the activities within the block. Variation in the strategy allows for more options. Hence, the focus of the present study is to strategically execute the basic sequence for the DSM blocks.

3. PROPOSED APPROACH - 'SPEED' OF ITERATION

The proposed execution strategy depends on the information or assumptions required to start/execute any activity [9], [17]. Assumptions made through tearing process have to be checked when updated information becomes available. During the process of checking, if the assumption made was not appropriate, the succeeding activities have to be repeated. If an activity is repeated whenever new information from any one of its predecessors is available, then it is 'Fast' speed of iteration. When the activities repeat as soon as new information arrives, more resources are expected for this case. Instead, if an activity waits for the information from all its predecessors and then repeats, it is referred as 'Slow' speed of iteration. 'Speed' of iteration arises, when; at least one of the activities in the block requires multiple information inputs. When all the activities in the block require single information input, 'fast' and 'slow' process will be the same.

The concept of 'speed' is illustrated in Figure 1. In this case, C is the start activity and when C is completed; activities A and E will be executed. Then, F will be executed. For 'slow' strategy, if

the assumption for C was inappropriate, C will repeat after the completion of A & F as seen in Figure 1(b). When the repetition of activities within the block is completed, information is passed on to activities outside the block. On the other hand, for 'fast' strategy, as soon as A is completed, C can repeat in parallel along with the execution of F, as in Figure 1(c). Here, information will be passed on simultaneously to activities outside the block also. Hence, more repetitions can occur within and outside the block for 'fast' if initial assumptions were made inappropriate [9], [17].

Here, C-AE-FB-D forms the basic sequence and can be determined with the help of standard DSM operations (partitioning & tearing). The 'execution sequence' is C-AE-F-C-AE-F-C-AE-F…BD for slow and C-AE-CFB-AECD-… for fast respectively.

The performance of 'fast' or 'slow' strategy can be evaluated by estimating its duration. As project duration is a function of the dependency relationships, number of assumptions, location of assumptions, etc. it is difficult to judge which 'speed' is better. Hence, there is a need for software tool to estimate the project duration for both the strategy and is presented next. The subsequent section elaborates on the Stroboscope model for estimating the duration.

4. MODEL IMPLEMENTATION

For simplicity, an illustration as shown in Figure 2 is explained throughout this section.

4.1. Parameters Involved – Inputs

Apart from the basic inputs to any DSM such as list of activities, and dependency relationship among the activities, the present model uses two other inputs – Rework probability values and probabilistic duration to estimate the project duration.

4.1.1. Rework probability values

These are numbers between '0'-'1' and can be included along the off-diagonal cells instead of 'X' marks [16], [17]. These values decide the choice

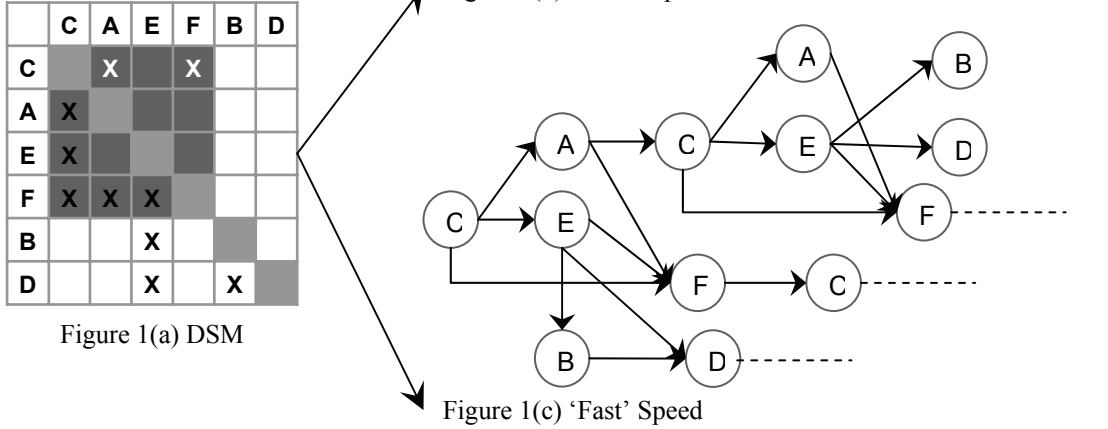


Figure 1(a) DSM

Figure 1(b) 'Slow' Speed

Figure 1(c) 'Fast' Speed

Figure 1 Iteration Strategy on 'Speed'

of repetition of the successor activity. In figure 2, consider the value of 0.1. This implies that if information from activity 'A' changes, then there is a 10% chance that 'B' will repeat.

	A	B	C
A	Pert[10,16,20]	0.5	0.5
B	0.1	Pert[17,20,25]	
C		0.9	Pert[26,29,32]

Figure 2 Partitioned DSM Sequence (Case-1)

4.1.2. Probabilistic duration values

The proposed model allows three point estimates for activity duration (PERT type) and is included along the diagonal cells of DSM. In figure 2, the value (Pert[10,16,20]) along the diagonal cell for A represents that the duration for A follows a three-point estimate of 10, 16, and 20 for BCV (best case value), MLV (most likely value) and WCV (worst case value) respectively.

4.2 Monte Carlo Simulation

Monte-Carlo simulation is attempted for estimating the project duration. Stroboscope, an acronym for STate and ResOurce Based Simulation of COnstruction ProcEsses has been selected to perform the Monte-Carlo simulation [18]. Among the several simulation languages, Stroboscope (ver 1,7,0) was chosen because of its ability to model complex operations and widespread usage.

For the stroboscope representation, information is assumed to be the resource flowing between the activities. Assumptions/uncertain information made for any activity is modelled as initial resource for the queues. The same stroboscope network was used to model 'fast' and 'slow' strategy based on flagging the input. Extra queues along with several 'controls' are introduced to control the flow of information during the 'slow' strategy.

The assumption made in this model is that the attributes (i.e. rework probability values and duration) do not vary with time. Further, rework duration is assumed to be the same as the normal duration for any activity. The above assumptions are made based on the following fact – Assumptions made for any activity can prompt the dependent activities to repeat or not to repeat. Further, based on the assumptions the activities may consume more duration or less duration than the normal duration. The PERT type duration distribution is assumed to take care of this uncertainty.

Once the stroboscope model is constructed, it is verified to determine whether the simulation model performs as intended. For verification, many trial (trace) runs were conducted.

4.3 Results

Table 1 presents the comparison of the results of the Stroboscope model for both the 'speed' (fast and slow).

Table 1 Comparison of the Results of Stroboscope Model for Fast and Slow (Case-1)

Strategy			Ave	Min	Max
Duration (days)		Fast	82.12	56.94	255.86
		Slow	89.20	58.09	345.16
No. of Repetitions for	A	Fast	2.20	0	9
		Slow	2.21	0	10
	B	Fast	0.22	0	5
		Slow	0.22	0	5
	C	Fast	0.20	0	4
		Slow	0.20	0	5

Observation of the results presented in Table 1 implies that 'fast' speed takes 82.12 days and the 'slow' speed takes 89.20 days. Further, the number of repetitions for the activities A, B, and C were almost the same for both the speed. Hence, for this particular case, the planner can select the 'fast' strategy for execution.

5. ANALYSIS & DISCUSSIONS

The above situation may not happen always. For the same example, consider an alternate sequence – CBA as shown in Figure 3. A comparison of the results for 'fast' and 'slow' for this DSM (Case-2) is displayed in Table 2.

	C	B	A
C	Pert[26,29,32]	0.9	
B		Pert[17,20,25]	0.1
A	0.5	0.5	Pert[10,16,20]

Figure 3 Partitioned DSM Sequence (Case-2)

Table 2 Comparison of the Results of Stroboscope Model for Fast and Slow (Case-2)

Strategy			Ave	Min	Max
Duration (days)		Fast	91.87	29.42	504.26
		Slow	61.24	30.14	156.28
No. of Repetitions for	A	Fast	1.09	0	18
		Slow	0.16	0	2
	B	Fast	1.88	0	18
		Slow	1.04	0	3
	C	Fast	0.29	0	5
		Slow	0.20	0	3

In this particular case, 'fast' speed consumes 91.87 days and the 'slow' speed was 61.24 days. The difference in the project duration for the 'speed' strategy is large in this case than the former one. Comparing the duration for both the cases shows that it is difficult to decide on the 'speed' strategy based on the basic DSM. Thus, there is a need for the Stroboscope model to decide on the 'speed'.

Further in table 2, all the activities for the 'fast' speed, repeated more number of times than for 'slow'. More number of activity repetitions implies requirement of abundant resources and project cost. Hence, for this particular sequence, the planners would select the 'slow' speed for execution.

From the above illustration it is clear that the choice of the strategy is directly dependent on (a) project duration, and (b) number of repetition of the individual activities. Analyzing the behaviour of the Stroboscope model, there are many attributes which influence the project duration These attributes include the basic sequence, the activity duration, rework probability values, etc. Research work in investigating the critical factors which govern the execution sequence and the resulting project duration is a potential area of future work.

Also, in the above two illustration, the authors have decided on the 'speed' strategy based on the output values (project duration and the number of repetition of activities). But the variation of the output values was very small in both the cases. This is because of the simplicity in the illustration.

It was stated earlier that it is difficult to decide on the execution sequence considering the basic sequence alone. So, stroboscope model has to be run each time for deciding the strategy. This process is tedious and not practical. Research investigation to determine the pattern recognition (may be by using Artificial Neural Network) is a critical area of future work.

Moreover, analysis of the schedule scenarios is theoretical and assumes no practical constraints. In reality, additional inputs such as resource availability, cost aspects, etc. is required for a practical analysis of the schedule and is an area of future work.

6. SUMMARY & CONCLUSIONS

The present study focuses on modelling iterations using DSM and simulation. Here, DSM determines the basic sequence and Simulation determines the execution sequence. The selection of 'speed' strategy is decided based on the project duration and the number of repetition of the individual activities. It was concluded that Stroboscope can be used for deciding the 'speed' strategy.

Illustration from the above example reveals that the proposed concepts can be applied to any design domain because of its simplicity. Even though the current example considers only one block, the same concept can be extended to multiple blocks. Further, the present approach is very basic and there is a need for further detailed research work to be done in this area as discussed earlier.

7. ACKNOWLEDGMENTS

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SCHEDULING MODEL FOR MULTIPLE DESIGN PROJECTS CONSIDERING UNCERTAIN DESIGN ITERATIONS

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ABSTRACT

Although slightly improving the control of the design schedule may greatly reduce the total duration of the project, but little effort has been made to control the schedule of the design project. Scheduling design activities 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. This work develops a simulation-based model to incorporate uncertain design iterations for generating the schedule of multiple design projects for a design firm. The proposed model is implemented and demonstrated by a case study.

KEYWORDS

Uncertain Design Iteration, Simulation, Design Schedule, and Design Process.

1. INTRODUCTION

A design firm often needs to allocate various types of design participants (such as architects, designers and draftsmen) to the multi-disciplinary activities of various design projects that are in various project stages (such as the proposal, conceptual / schematic design, detailed design, and construction stages). Effectively assigning the design participants depends on how the design activities are scheduled.

Scheduling of design activities for multiple projects is complex because design activities frequently depend differently on information about each other. Namely, the design process involves various iterations across activities [1-6]. Moreover, the fact that the numbers of iterations and the durations of design activities are uncertain makes difficult to identify the precedence relationships among activities and to evaluate the durations of the design projects. This study develops a simulation-based scheduling model to effectively allocate design participants for multiple design projects. Particularly, simulation algorithms are proposed to model the uncertainties of design iterations and activity durations.

2. PAST RESEARCH

During the conceptual and schematic design stages of a building project, a chief designer (architect / engineer or A/E) gathers information from a wide range of disciplines; candidate solutions are proposed, and new states are generated from the current ones based on the information available to meet the owner's requirements, including, for example, the budget and general spatial arrangements [4,7]. These two early stages ensure that the design deliverables fulfill the owner's demands.

In the detailed design stage, the required design work is stated in greater details; the design deliverables must be delivered to prevent future construction work from being delayed. Much research has been done to improve the control of the detailed design process, increasing the effectiveness of the control of the design duration. For example, Sanvido and Norton proposed a

building design process model that specified the keys for a successful design [8].

Steward considered design iterations and defined possible relationships between a pair of design activities - dependent, independent (parallel) and interdependent (coupled) [9]. Austin et al. elucidated a planning methodology (Analytical Design Planning Technique; ADePT) for planning building design [1-3].

Wang and Dzeng applied a modified cluster identification algorithm to evaluate the dependencies of design activities on information, to enable activities to be regrouped to support the assignment of design activities [10]. Wang et al. presented causes and various types of design iterations for a building project and developed an innovative simulation- based model to incorporate the design iterations to generate a schedule for a design project [6]. Finally, Cho and Eppinger proposed a DSM-based process model using simulation for managing industrial design projects [5].

3. PROPOSED MODEL

The proposed model extends a previous study of Wang et al. [6] to deal with multiple design projects, to incorporate the uncertainties of design iterations and the uncertainties of activity durations, and to offer a cost analysis. The model, developed from the perspective of a design firm, includes four major phases (Fig. 1)

3.1 Phase I: Representing the Design Process for Multiple Projects

A common design activity usually has deliverables such as drawings, reports, and calculations. For instance, the design activities considered herein include floor plan design and exterior elevation design activities, with the deliverables “plans” and “elevations”, respectively. Another type of design activity, called review/approval activity herein, does not have definite outputs and it involves in certain amount of discussions, clarifications and even revisions. A design dependency is the logical relationship between activities. The dependency between activities, A→B, demonstrates that the information flow delivers the design deliverables from A to B.

Based on the identified activities and their dependencies, dependency structure matrix (DSM) is applied to help identify design iterations with complete loops. Steward [9] and many other publications provide details on the DSM methods. After iterations with complete loops have been found, the model user must explore whether incomplete design loops are present, based on past experience.

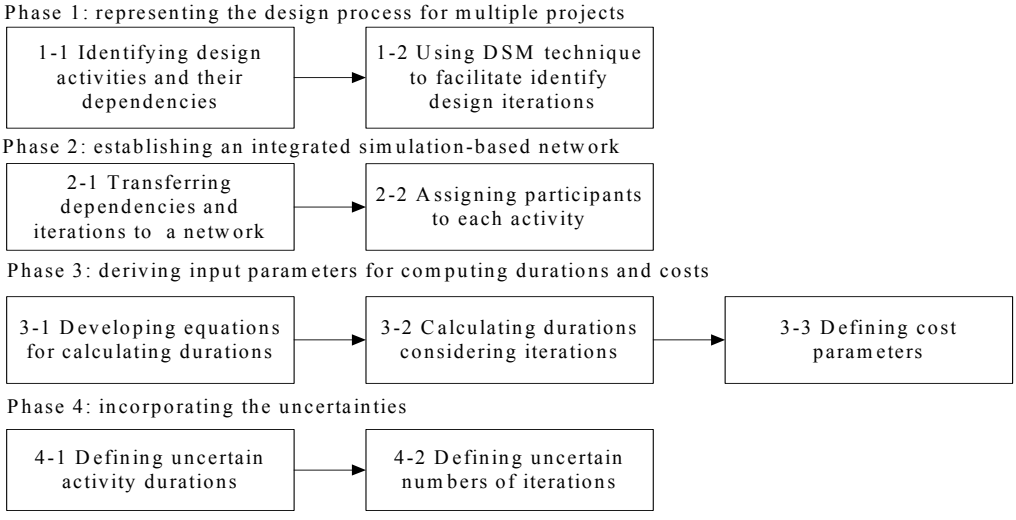


Figure 1 Proposed Model

3.2 Phase II: Establishing an Integrated Simulation-Based Network

Phase I identifies dependencies and iterations. Phase II establishes a simulation-based network, and assigns design participants (such as architects, designers and assistant designers) to each activity. The proposed model uses the symbols of Stroboscope [161 to represent the simulation-based network of schedule. In Stroboscope, "Combi" nodes refer to design activities that start when specific conditions are met. Each Combi node is shown with a cut at the top left-hand corner of a square box. Queue nodes hold idle design resources. Each queue (indicated by a "Q" in the network) is related to a particular class of resource. A link (→) connects two network nodes and presents the direction and type of design resources that flow through them. The node at the tail of the link is the predecessor, and that at the head (indicated by the arrow) is the successor.

This step, *assigning participants to each activity*, is to allocate the type and the number of participants to each activity.

3.3 Phase III: Deriving Input Parameters for Computing Durations and Costs

The first step of phase 3 is *developing equations for calculating durations*. Regarding the computations of the durations of design activities, two methods are proposed. The first method is developed to handle the common design activities that produce design deliverables, and the second method is to deal with the review/ approval activities that have no explicit design deliverables.

The second step of phase 3 is *calculating durations considering iterations*. The time required to complete a design activity i ($D_{i(n)}$) with n iterations, is the sum of three parts - the time (d_i) required to complete the amount of deliverables, the time (dd_i) required to process the received and the to-be-delivered deliverables, and the time ($\sum_{n=1}^{N} IterD_{i(n)}$) required to rework drawings due to iterations.

The third step of phase 3 is *defining cost parameters*. The proposed model offers a cost analysis by assigning wage rates (dollar per hour) to participants. The cost per participant equals the period of his or her participation (working and idle hours) multiplied by his wage rate. The total design costs are the sum of the participant costs. A design manager can thus make an improved decision in allocating design participants to activities, to ensure satisfactory project duration and cost.

3.4 Phase IV: Incorporating the Uncertainties

The first step of phase is *defining uncertain activity durations*. In computing the duration of activity i (i.e., ($D_{i(0)}$)), the quantity of required deliverables (Q_i) is assumed to be certain. However, the value of design productivity (P_{ij}, hour per unit) is assumed to be probabilistic. The proposed model uses three-point estimates (optimistic, most likely, and pessimistic unit rates) to obtain a Beta distribution for the productivity for each participant j in each activity i. Notably, various participants with different degrees of productivity are involved in completing the drawings of an activity.

The second step of phase 4 is *defining uncertain numbers of iterations*. In the design process, a certain amount of design information may flow among activities several times until design deliverables are compatible or regulatory requirements are met. Whether an iteration with a complete or incomplete loop will arise is assumed to be probabilistic. The model also applies three-point estimates (lowest, most likely, and highest probabilities; between 0 and 1) to obtain a Beta distribution for the occurrence of an iteration loop x. A random variable ($Occur_x$) for each iteration loop is devised. For example, the model user may specify that the lowest, most likely, and highest probabilities for the occurrence of an iteration loop x are 0.2, 0.4, and 0.6, respectively. Then, in each simulation run, a value will be drawn from the distribution (0.2, 0.4, 0.6) to represent the probability that iteration loop x will occur.

Additionally, the value of $IterDR_i$ (the fraction of the developed drawings associated with activity i that must be reworked at an iteration) is also treated as an uncertain variable. Again, the model utilizes three-point estimates (lowest, most likely, and highest fractions; between 0 and 100%) to obtain a

Beta distribution for indicating the fraction (or percentage) of $IterDR_i$.

4. IMPLEMENTATION

A simulation language, Stroboscope [11], is adopted to implement the simulation-related algorithms in the proposed model. All the abovementioned input parameters and derived equations must be suitably coded using Stroboscope statements. In this investigation, Stroboscope was run in the Windows XP environment, with a P3 850 CPU and 256 Mbytes of RAM. Five thousand simulations runs took under one minute for the case study.

5. EXAMPLE

5.1 Project Description

A medium-size architectural design firm that is located in northern Taiwan is used for demonstrating the proposed model. This firm must handle six design projects in two months (i.e., about 480 working hours). These design projects are related to 10~12-floor office buildings. Projects A, B and F are in construction phase and require certain design work caused by owner-directed change orders. Project C, D and E are in the construction tendering phase, conceptual design phase, and detailed design phase, respectively. Notably, the design work of these six projects involves four design disciplines - architectural, structural, HVAC and electrical.

5.2 Inputs

First, the design activities and their dependencies must be identified (Step 1-2). 79 activities are indicated in six projects. There are 1, 1, 10 (8 common activities and 2 review/approval activities), 30 (26 common activities and 4 review/approval activities), 34 (29 common activities and 5 review/approval activities), and 3 activities (2 common activities and 1 review/approval activity) are identified for projects A, B, C, D, E, and F, respectively. Four different disciplines perform these 79 activities.

The input data for structural, HVAC, and electrical design can also be provided in a similar manner. (These data are not displayed here due to the limitation of paper length.) Additionally, nine design participants are assumed to work on these projects. Table 1 displays the number and wage rate (US dollars per person per hour) for each participant. (Step 3-3).

5.3 Evaluations

Based on the identified precedence relationships between activities, the DSM is applied to search for iterations with a complete loop (Step 1-3). For example, Figure 2 presents the partitioned matrix for project E. Each "X" in the matrix indicates that the activity on the left-hand side depends on the activity at the top of the matrix. This partitioned matrix demonstrates that 34 activities of project E contribute to three iterative loops (iterations R, Y, and U with complete loops).

There are eight iterations (iterations R, S, T, U, V, W, Y, and Z) in the six projects. Six iterations (R, S, T, U, Y, and Z) with complete loops are identified by DSM, while two iterations (V and W) with incomplete loops are indicated by the model user.

Table 1 Number of Persons and Wage Rate of Each Design Participant

Participants	Number of persons	Wage rate ($US / hour - person)
Architectural discipline		
Architect	1	50
Designer	1	30
Draftsman	1	23
Structural discipline		
Structural consultant	1	40
Structural engineer	1	26
HVAC discipline		
HVAC consultant	1	38
HVAC engineer	1	25
Electrical discipline		
Electrical consultant	1	36
Electrical engineer	1	28

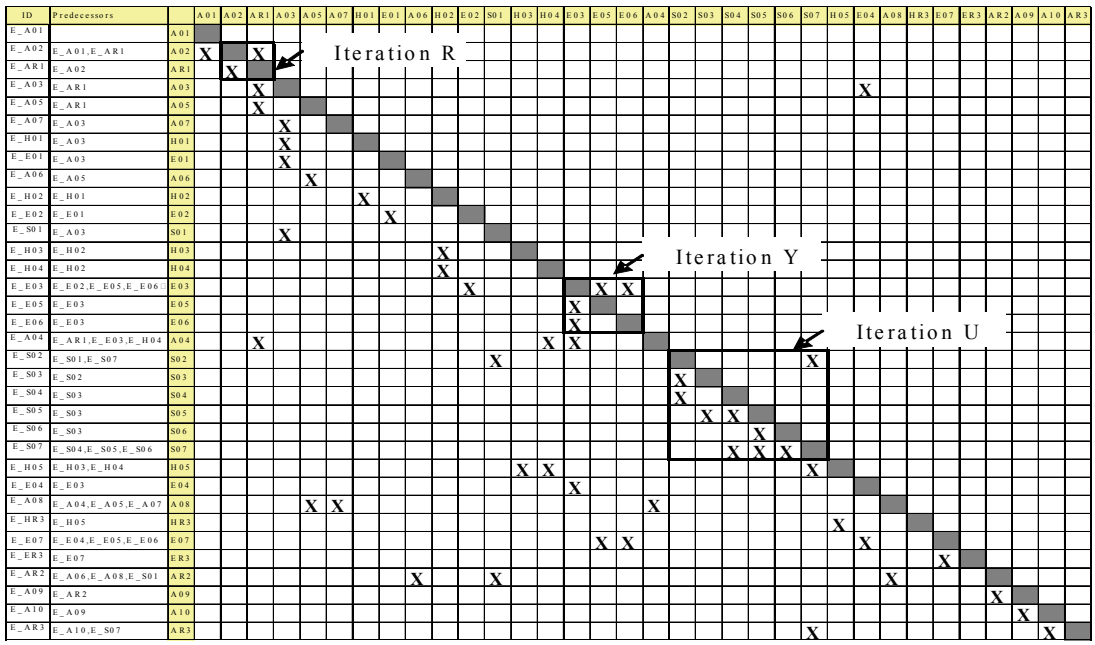


Figure 2 Three Iterations Identified by DSM in Project E

Figure 3 depicts the established simulation-based network for the six design project (Step 2-1). The network incorporates the 79 activities (represented by Combi nodes), 9 participants (represented by Queue nodes) and the dependencies among activities (represented by links). Additionally, eight Dynafork nodes (each represented by a cycle enclosing five rays) that have routing capabilities for activating downstream activities control the occurrence of the eight iterations. All small Queues shown in the network are used only to control the resource flows.

5.4 Results

By assuming that one of each type of participant is present and simulation is run for 5,000 times, the duration of the design work of six projects is 466.6 hours (approximately 58.3 working days, eight hours per day).

The simulation enables the model to evaluate the utilization rates of the participants (stored in Queues). That is, the working time, idle time, total cost and idle cost of each design participant involved in the six projects can be calculated. For instance, the idle times of the architect, the designer and the draftsman in performing the architectural activities are 257.0, 76.7 and 165.3 hours, respectively. Thus, a design manager may assign additional design activities (of the same project or other projects) to the architect who is very idle.

Finally, comparing with the scenarios with and without iterations, the consideration of iteration has increased the expected duration from 426.3 to 466.6 hours. The increase is about 40.3 hours (=466.6-426.3) or 9.5% (=40.3/426.3). Additionally, using the 2 months (480 hours) as the deadline, the probability of meeting that deadline is about 66.4% (considering iterations).

6. CONCLUSION

This work devises a new model to generate schedules for multiple design projects. With the support of simulation technique, the model also considers the uncertainties on the durations of design activities and the occurrences of iterations for evaluating the risk of completion durations of design projects. Moreover, cost information with respect to different project durations can allow a trade-off analysis between the cost and time.

7. ACKNOWLEDGMENT

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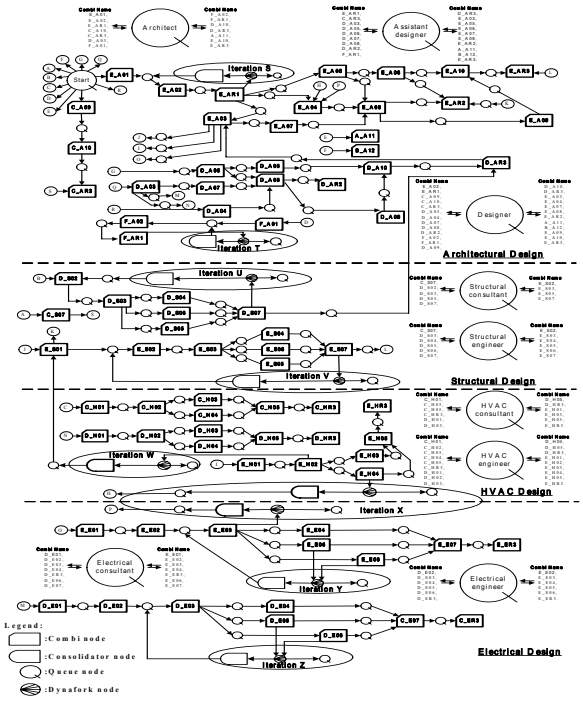


Figure 3 Simulation-Based Network of the Six Projects

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TIME SERIES ANALYSIS OF CONSTRUCTION COST INDEX USING WAVELET TRANSFORMATION AND A NEURAL NETWORK

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ABSTRACT

Construction Cost Index (CCI) is widely used to analyze the construction cost variation in time. It can convert the present construction cost to the future or to the past. The current practice of the future cost estimation is simply an extrapolation of the past CCI, which often leads to the inaccurate estimation of future construction cost. This paper presents a new CCI forecasting model using wavelet transformation and an artificial neural network. Preliminary tests showed that the proposed method produced the short-term range of a future CCI with a greater accuracy as well as a higher reliability compared to existing methods.

KEYWORDS

Construction Cost Index, Forecasting, Time Series Analysis, Wavelet Transform, Neural Network

1. INTRODUCTION

In cost estimating practices, careful consideration should be given to predicting the cost change of a construction project. Labor, material and equipment cost tend to rise over time, so a proper adjustment needs to be made to the initially estimated construction cost. Construction Cost Index (CCI) is a kind of price index for the construction industry. It is widely used for its ability and simplicity to convert the present construction cost to the future or the past. Major cost items are monitored and weighted, then processed to a CCI. Thus, a CCI is representative of general construction cost changes in a region.

A range of efforts have been made to produce and forecast a CCI. Each country or region has their own CCI different from those of other regions. The local social and economic situations are reflected in the different CCIs. The current practice of a CCI prediction, however, is largely based on a simple extrapolation of the past CCI. This simple extrapolation approach often leads to the inaccurate estimation of future construction cost. Thus, a strong need exists to develop a more accurate cost prediction method for CCI. A back-propagation neural-network model was developed to predict the change in the ENR construction cost index for one month and six months ahead (Trefor, 1994). However, the prediction accuracy of the neural network model was not superior to either exponential smoothing or linear regression methods.

The objective of this study is to suggest a new CCI forecasting model that can produce the better

accuracy compared to existing methods. When it is possible to accurately predict the future CCI, there exists a better chance to get accurate estimation of future construction costs. To this end, wavelet transformation and artificial neural networks constitute the proposed methodology. Wavelet transformation is used to get rid of unnecessary noisy data from the past construction cost indices, while an artificial neural network is used to forecast the future construction cost index based on the refined past index data.

2. TIME SERIES ANALYSIS OF CONSTRUCTION COST INDEX

2.1 Construction Cost Index Variations

This study used the CCI data published in Korea. The official CCI data have been published since February 2004 by the Korea Institute of Construction Technology (KICT). This CCI is a analytic statistics data, based on a Korea Producer Price Index and an Inter-industry Relation Table. However, the authors extended time range to 1995 using the KICT methodology to secure sufficient amount of data for prediction model development. Figure 1 shows the monthly change in CCI for 140 months from January 1995 to July 2006.

As shown in Figure 1, the CCI increases over time, however it shows many small fluctuations in short intervals such as several months. For 84.9% of the data, monthly change ranges between 0 to 1%, however some cases differs by over 3% reflecting the economic situations at that particular times. For example, the leap increase around 1998 was the result of critical changes due to the financial meltdown that severely attacked Asian countries. As shown, construction costs can vary over time with changes in demand, economic conditions, prices and etc. (Trefor, 1994).

2.2 Data De-noising

Wavelet transformation is a "method that analyses time-frequency localization with fixed window size and with changeable time-windows and frequency-windows" (Meyer, 1993). By using wavelet analysis, longer time windows can be used to detect low frequency information, while shorter time windows are used to detect high frequency information. Wavelet transformed signal is decomposed into components that different scales. This offers a "method for a local outlook of the signal, a multi-scale outlook, and a time-scale analysis" (Misiti et al., 1996). Thus it can be used as a tool for performing a wide range of tasks which include: detecting discontinuities in signals, detecting trends, analyze time-frequency, de-noising and compression of signals (Khaled and A. Ramachandra, 2000).

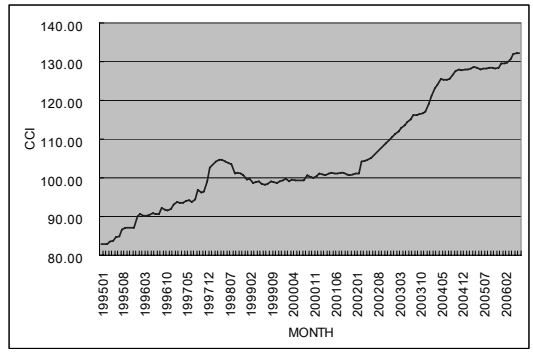


Figure 1 Construction Cost Index (KOREA)

As stated, CCI varies with many factors; some factors have influenced on the CCI for a longer time of period, some for only short time period. The latter particularly results in noisy data in the process of predicting the future CCI, which disallows accurate prediction. In this study, wavelet transform is used to de-noise raw CCI data. The raw data was first de-noised by fixed form thresholding in the wavelet domain. Figure 2 shows the de-noised data compared with origin data. This processing was conducted using a MATLAB 7.1 wavelet toolbox. Monthly difference of de-noised CCI data was used as input data for a back-propagation neural network model.

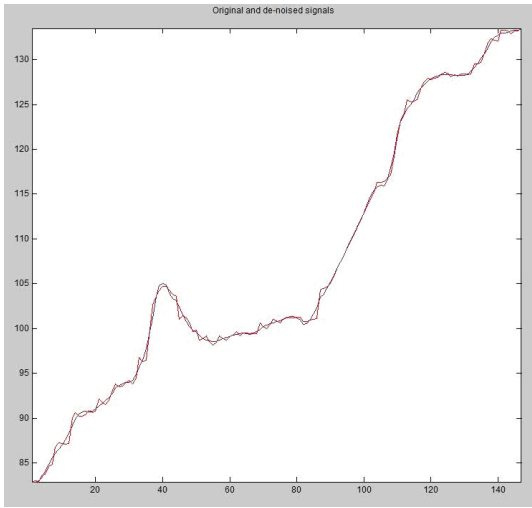


Figure 2 Original and De-Noised CCI
(X axis: Month, Y axis: CCI)

2.3 Prediction Using Neural Network

Artificial Neural Networks is a model that mimics human nerve system. In this study, the Back-Propagation Network is used for forecasting future CCI. As previously mentioned, de-noised CCI data's monthly difference were used for the neural network. The number of hidden layer is set to be 2, and the mean square error is used as a performance function for error evaluation.

A total of 147 months of CCI data were used for neural network training and testing (January 1995 to March 2007). Based on the de-noised CCI data, a total of 130 training sets and seven testing sets were prepared as follows:

- CCIs for month 1 to 10 are used as input data, and the 11th CCI is used for output data; the total of 11 monthly CCIs constitute a training set.
- CCIs for month 2 to 11 are used as input data, and the 12th CCI is used for output data; the total of 11 monthly CCIs constitute a training set.
- In this way, a total of 130 training sets are prepared and used to train the back propagation neural network.
- CCIs for month 131 to 140 are used as input data, and the 141st CCI is used for output data; the total of 11 monthly CCIs constitute the first testing set.
- CCIs for month 132 to 141 (the 141st CCI is the one calculated from the trained neural network) are used as input data, and the 142nd CCI is used for output data; the total of 11 monthly CCIs constitute the first testing set.
- CCIs for month 133 to 142 (the 141st and 142nd CCI are the ones calculated from the trained neural network) are used as input data, and the 143rd CCI is used for output data; the total of 11 monthly CCIs constitute the second testing set.
- In this way, a total of 7 testing sets are prepared to test the trained neural network.

Table 1 shows that comparison of predicted CCI and actual CCI of the seven test sets.

Table 1 CCI Comparison

Month	Actual CCI	Predicted CCI	Difference
Sep.2006	133.3	133.4	0.1
Oct.2006	133.3	133.6	0.3
Nov.2006	133.2	132.9	-0.3
Dec.2006	132.9	133.1	0.2
Jan.2007	133.2	133.4	0.2
Feb.2007	133.2	133.7	0.5
Mar.2007	133.5	134.0	0.5

2.4 Comparison With Other Forecasting Techniques

To check the usefulness of the suggested model, the results were compared with those of three other forecasting techniques: a moving average method, an exponential smoothing and a neural network without de-noise processing. A moving average method and an exponential smoothing are widely used due to its simplicity, computational efficiency and reasonable accuracy (Montgomery and Johnson, 1976). Prediction results were obtained using the four models for the same test period (7 months) with the same input data.

Figure 3 shows the comparison graphs of actual CCI, the proposed model, a moving average method, an exponential smoothing and a neural network without de-noise processing. Table 2 shows the sum of the squares of errors (SSE, Eq.1) of each model.

$$SSE = \sum_{i=1}^{n} (P - A)^2 \quad (1)$$

(P= Predicted CCI by each model, A= Actual CCI)

The proposed model cannot produce as accurate predictions as actual data (Table. 2), however it gives the most accurate results among the four prediction models. It is noticeable to note that the neural network without denoising process produced the worst results. Wavelet-based denoising process is a powerful tool to increase the CCI prediction accuracy.

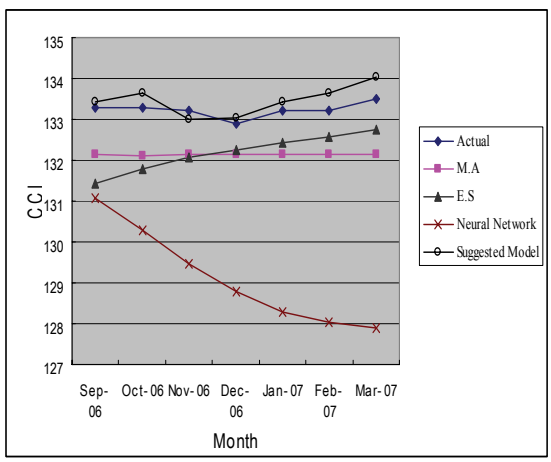


Figure 3 Comparison Graph

Table 2 SSE Comparison

Forecasting technique	SSE
Moving Average (2months)	8.6
Exponential Smoothing	9.1
Neural Network	127.04
Neural Network with De-noise	0.72

3. CONCLUSION

The objective of this study is to suggest a new model for accurately predicting a future CCI. In construction, the ability to predict trends in prices is very important for more accurate bids and reliable planning. Although the back-propagation neural network is a powerful tool to recognize patterns, it was inferior at CCI prediction due to the complex patterns and noisy signals of the periodic CCI data. The proposed model relied on the back-propagation neural network to predict a future CCI, but input CCI data is equipped with the pre-processing stage to get rid of unnecessary noisy data. The wavelet-based denoising process produced a much better chance of making more accurate prediction of future CCIs.

In this study, the new model was applied only for the prediction of seven CCIs. Further studies are required to verify and improve the model. The more training and testing sets will be used to produce a viable model that can predict the future CCIs in an accurate, reliable, and efficient way.

4. ACKNOWLEDGMENT

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DEVELOPMENT OF IMAGE PROCESSING METHOD FOR HIGH QUALITY PIPELINE INSPECTION

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ABSTRACT

Sewer pipelines are buried underground and often forgotten until serious failure happens. Effective and reliable sewer system management is very important for the safe and clean environment. In order to maintain the intended capacity of pipes, effective maintenance based on accurate condition assessment is required. This research suggests a new method that uses digital still images to overcome the limitations of common CCTV pipeline inspection systems. As a result high quality images are obtained for accurate and effective condition assessment of pipelines.

KEYWORDS

Sewer Inspection, Digital Image Processing

1. INTRODUCTION

According to the Ministry of Construction and Transportation of Korea (MOCT), 819,558-km of roads and seven major underground infrastructures (water main, sewer lines, large area water main, gas, heat, electricity, and communication lines) should be electrically filed in a form of database. Out of 81,9558-km lines, 88.4% (724,311 km) has already been stored in DB and used by public and private users. About 320 million US dollars have been invested on the development of the GIS systems for this system development [1]. However, the DB includes only the quantitative data such as location of pipes, installed depth, material type, installation date, etc.

The qualitative data such as the condition of pipes is not usually included in the DB. Since the condition of pipelines is often more important than location of pipelines, an effective and efficient method to collect the pipeline condition is critical in pipeline management DB.

The most common method of pipeline inspection is using a remote-controlled-machine equipped with a CCTV (Closed Circuit TV), which, however, has many limitations to accurately inspect pipeline condition. In this research, a new approach to inspect the pipeline is developed. The suggested system takes pictures of inner surface of the pipe and produces high quality unwrapped images.

1.1. Limitations of Typical CCTV Inspection

In case of a typical CCTV, since the camera looks at the end point of the pipe, the locations of the defects and distance-readings are often different. In addition, the quality and accuracy of the inspection is highly dependent on the operator's skill and experience (Fig. 1). Various difference light conditions and the angle of the camera lens make various optical conditions making the inspection unreliable and unstable. The skill of the operator is the major factor of the accuracy and completeness of the inspection result.

Although recent pan-and-tilt cameras have overcome some limitations of simple front-viewing CCTV probes, still the operator's

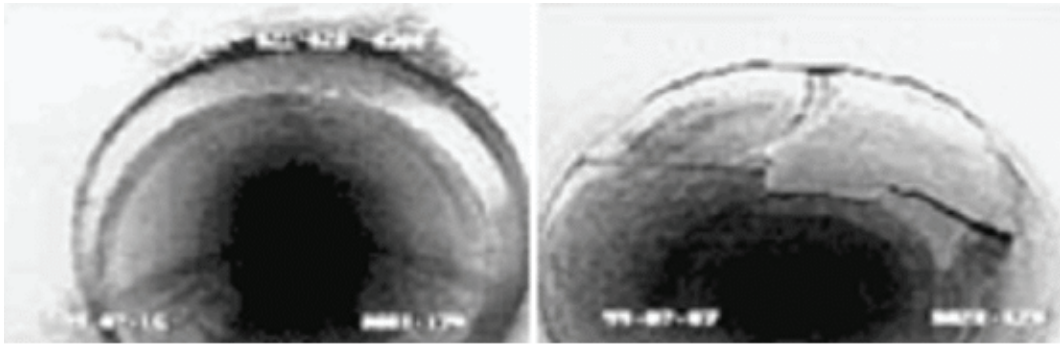


Figure 1 Stop and Pan-and-Tilt Images

skill is very important because the probe has to be stopped for pan-and-tilting.

Whether it is a front-view only camera or a pan-and-tilt camera, the quality and accuracy of the inspection highly depend on the skill and the experience of the operator. If the operator misses a defect, i.e., no stopping and pan-and-tilting, the defect would not be recorded and forgot until a new inspection is performed.

OYO-USA has developed a new type of sewer inspection system called SSET, which is equipped with a fish-eye lens to get a direct view to the pipe wall. It uses single line of image pixels to construct unwrapped circumferential images of inner surface of pipe wall. However, the fish-eye lens method for digital pipe line scanning had limitations in image quality and scanning speed.

2. DEVELOPMENT OF DIGITAL SCANNER FOR SEWER PIPELINE INSPECTION

2.1 Image Acquisition and Processing

In this research, a new approach is developed to overcome the limitations of SSET. The developed system uses larger areas of side view and constructs high quality stitched side view images.

As shown in the Figure 2, a plastic pipe was built to test the image acquisition system. Numbers are printed on the pipe wall to indicate the right location and stitching discrete images. Images are taken in several discrete blocks and unwrapped image result is presented in the Figure 3 and Figure 4.

2.2. One Lens System for Both Front and Side View

In order to obtain front view as well as side view simultaneously, and for better efficiency, one-lens system is developed, which is equipped with a common digital camera and specially designed mirror system to take both side and front view at the same time (Fig. 5).

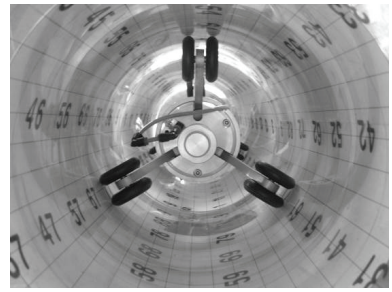


Figure 2 Image Acquisition Test Pipe

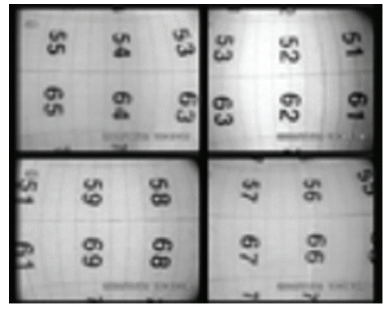


Figure 3 Before Image Stitching

Initially, before the one lens one CCD system was developed 4CCD system was developed. Scanned images of inner surface of pipe wall are processed

and opened on a 2-D domain and stitched carefully. Figure 5 shows the 4 CCD camera system for 3-D image mapped on 2-D space. Gray areas the scanned areas by 4 CCD cameras and dark areas are the overlapped area the stitching reference.

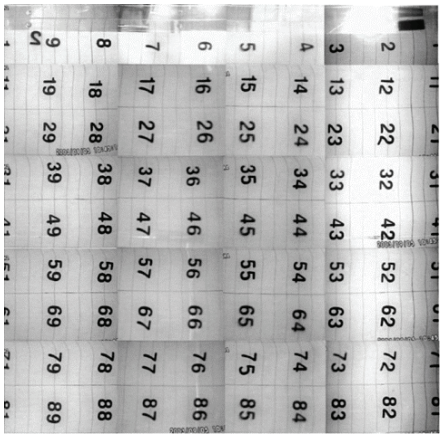


Figure 4 Stitched Image Mosaic

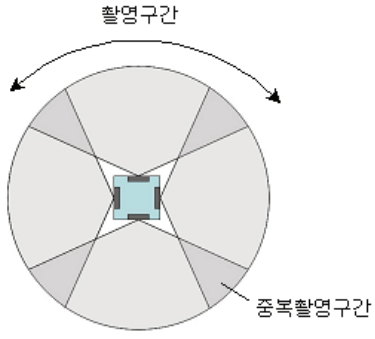


Figure 5 4CCD Scanning

However, this 4 CCD system has many difficulties in registration of the four different images. It required heavy load on manual image processing work.

One CCD system was developed based on the experience of 4CCD system. One CCD takes pictures both front and side view. In the Figure 6, CCD is located on the left side of the lens and the pipe object would be on the right. Side wall of inner surface of the pipe and the front view are obtained through this lens system. The resulting image is shown in Figure 9. Figure 7. shows the CCD camera and the developed lens.

When the camera scans the inner surface, the field of depth from the location of the camera to the object varies along with axial direction of the pipe. The distance calibration has to be performed to get the undistorted side view images. As in Figure 8, trapezoidal shaped images are obtained and it is process to be mapped on rectangular surface. [2],[3]

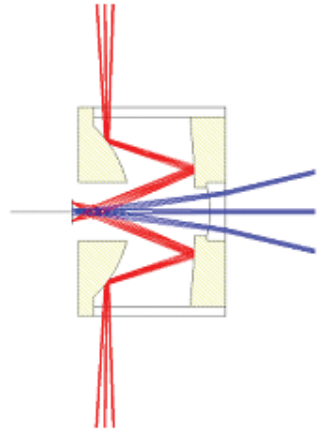


Figure 6 Design of the One-CCD System Lens

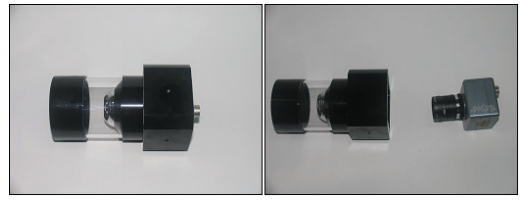


Figure 7 CCD Camera and Lens System

Once the images are calibrated it will be look like as shown in Figure 9. Straight lines in the pipe are shown straight. Camera collects certain distance of the pipe images. In order to develop a one continuous unwrapped image of the pipe, multiple stripes of the calibrated images are put together (registration) into one. The resulting image is shown in Figure 10. In this research, registration is completed by semi-automatically while distortion calibration is done automatically. In order for the perfect registration, a reference point (known objects) must be provided. However, the shapes in pipe wall usually do not have unique shape to be used as reference point. In the experiment, numbers on the pipe are good reference points, but

in the real pipe, there is no number. Authors are current putting efforts to use distance reading as the registration reference. By use of laser distance meter, exact location of the probe is obtained and the image strips are stitched without reference point.

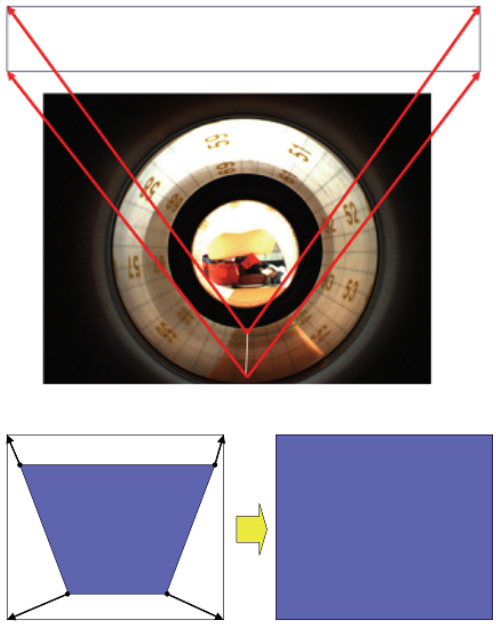


Figure 8 Image Distortion Calibration

3. CONCLUSION

In this research, a new system is developed by use of the image processing techniques. The image acquisition system is developed that inspects the inner surface of pipe. Side view unwrapping and stitching technology using image process techniques are developed which delivers high resolution image data.

Digital image scanning method is an innovative method for the pipe condition assessment. High quality images would bring dependable condition assessment of the pipes as well as the convenience of digital technology.

There were many barriers to make the unwrapped continuous image of the pipe line. Calibration of the distorted images is a difficult problem to solve, and the registration of processed strips of side wall is another difficult task. Since the pipe images usually does not have the distinct shapes to be used as reference point, instead of using reference point for the registration, accurate distance meter to get the exact location of the probe in the pipe is the better option. In this research project (will be continued until end of 2008) engineers will put effort mainly on the accuracy and reliability improvement of distance readings for the accurate image registration.



Figure 9 Adjusted Sample Image Strip

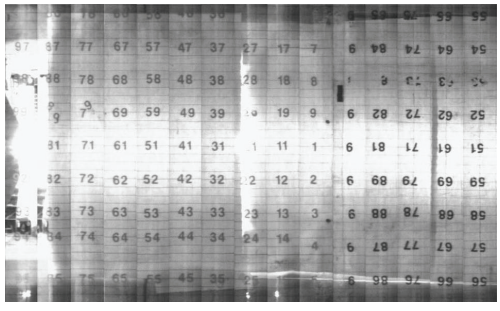


Figure 10 Side View Image Using One-Lens System

4. ACKNOWLEDGMENT

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PERFORMANCE EVALUATION OF HOT SPOT EXTRACTION AND QUANTIFICATION ALGORITHMS FOR ON-LINE WELD MONITORING FROM WELD THERMOGRAPHS

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ABSTRACT

The quality of welded steel structures play an important role in determining the reliability of a building. Weld quality is affected by Incomplete Penetration, which is a most commonly occurring defect in welds. An automated adaptive welding system if developed can correct the deviation in the welding current on-line so as to adjust the depth of Penetration to provide defect free welds. This system requires an on-line weld-monitoring sensor, efficient image processing algorithm for defect identification and neurofuzzy control software for correlating the defect characteristics with deviations in physical parameters. Infrared Thermography is the best-suited sensor for on-line weld monitoring and continuous assessment of welds. Incomplete penetration affects the hot spot of the thermograph and hence hot spot quantification describes the defect effectively. Three different algorithms namely conventional algorithm, region-growing algorithm and Euclidean distance based color image segmentation algorithm are developed for hot spot quantification. The paper compares the effectiveness and suitability of these algorithms for on-line weld monitoring.

KEYWORDS

Thermographs, Incomplete Penetration, Region Growing, Color Segmentation

1. INTRODUCTION

Gas Tungsten Arc Welding (GTAW) commonly referred, as Tungsten Inert Gas (TIG) welding is best suited for precision welding of steel structures. It is an arc welding process wherein coalescence is produced by heating the job with an electric arc struck between a Tungsten electrode and the job. A shielding gas is used to avoid atmospheric contamination of the molten weld pool. In spite of the numerous advances in development of automatic weld manufacturing equipments, failures do occur and weld is still considered to be the weakest portion. Incomplete Penetration affects the quality of weld ands is a serious defect. Conventionally, the quality of the

weld is ascertained only after the welding has been completed through the use of Non Destructive Testing (NDT) such as ultrasonic or radiography. Since each of these techniques is applied only after the welding is completed, a lot of time, material and manpower are wasted before one comes to know about the soundness of the weld.

These limitations can be overcome if the weld is continuously monitored in real time for the assessment of defects and their automatic elimination by on-line control of the welding parameters. It is achieved through Adaptive welding techniques, which involve suitable sensors, image processing algorithms for defect feature extraction, extracting relationship between the defect features and physical parameters responsible for the defect and neuro fuzzy control software for obtaining the deviations in the weld physical parameters.

Infrared thermography is the best-suited sensor for on-line weld monitoring as the sensor measures the temperature variations in the weld pool during the welding process. Numerous groups worldwide have used Infrared investigation techniques in the inspection of subsurface defects and features, thermo physical properties, coating thickness and hidden structures. Thermographs are used to the control of welding process problems, such as arc misalignments [1]. Variations in plate thickness, shielding gas composition and minor element content causes weld geometry changes. These parameter deviations are detected from temperature gradients obtained from infrared data [2]. Infrared sensors are used for on-line weld geometry monitoring and control. Infrared thermography is the widely used method for Non-Destructive Testing. Thermography offers non-contact, wide area detection of subsurface defects. Different passive and active thermographic techniques are used for defect detection. Active techniques include Pulse thermography, Lockin thermography, Pulsed phase thermography and vibrothermography [3-5]. Infrared sensors are best suited for weld quality detection as the perturbations that arise due to variations in arc positioning, heat input and the presence of contaminants distinctly manifests itself as differences in the spatial and temporal surface temperature distributions. Hence image analysis techniques can be developed to quantify the changes in the temperature distribution there by enabling adaptive welding techniques for automated weld control [6]. Quantification of thermographs is achieved by image processing algorithm through histogram equalization, image segmentation and morphological image processing. These features extracted from the algorithm are then used for on-line weld monitoring to produce defect free welds [7].

After acquiring thermal images, features corresponding to weld defects are extracted. These feature vectors are related to the corresponding deviations in physical parameters responsible for the defect. With this mapping, the respective physical parameter is then controlled to produce defect free welds. This paper proposes three different image-processing algorithms for hot spot quantification. The paper also compares the performance of these algorithms and examines the suitability of these algorithms for on-line weld monitoring.

2. THERMOGRAPHS DEPICTING LACK OF PENETRATION

Incomplete Penetration occurs when penetration of the weld metal into the joint is insufficient compared to what is specified for the joint according to the welding symbol. It is caused by too low welding current or too high welding speed or incorrect joint geometry. It is a serious defect as it can contribute to failure as stress raisers and least resistant path.

During the welding process, the high temperatures associated with the arc and appropriate thermo physical properties such as thermal diffusivity cause strong spatial temperature gradients to occur in the weld pool. The thermal maps produced by infrared thermal imaging instruments are called thermographs. Thermograph is defined as a 2D radiance function g(x, y), where x and y denote spatial coordinates and the value of g at any point is proportional to the radiance or energy emitted from the scene at that location. Traditionally, low intensities are represented by dark shades and high intensities by bright shades. With the decrease in degree of penetration or increase in Lack of Penetration, the area, major axis length and minor axis length of the hotspot also decreases. Thermographs for three different depths of

penetration namely 100%, 80% and 60% are shown in Figure 1, Figure 2 and Figure 3.

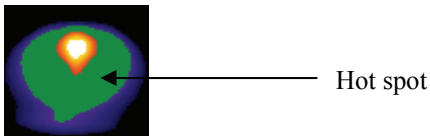


Figure 1 Thermograph Depicting 100% Penetration



Figure 2 Thermograph Depicting 80% Penetration



Figure 3 Thermograph Depicting 60% Penetration

3. DIGITAL IMAGE PROCESSING ALGORITHMS

A digital image is defined as a two-dimensional function, f(x,y) where x and y are finite values representing spatial co-ordinates, and the amplitude of f at any pair of co-ordinates (x,y) is called the intensity or gray level of the image at that point. F is also a finite quantity. These elements are referred as pixels. Developing suitable image processing algorithms identifies the region of interest.

3.1 Conventional Image Processing Algorithm

The developed algorithm involves image segmentation through edge detection, followed by dilation, region filling and erosion. Segmentation subdivides an image into its constituent regions or objects. The level to which the subdivision is carried out depends on the problem being solved. Edges of the hotspot region are obtained by using Sobel masks. From the edge-detected image, the hotspot is obtained through morphological image processing.

Mathematical morphology is for extracting image components that are useful in the representation and description of region shape such as boundaries, skeletons etc. It involves dilation, region filling and erosion. Dilation is for bridging the gap between the pixels in an image. With A and B as sets in Z^2, the dilation of A by B is

$$A+B=\{z\backslash(B\hat{})_z nA \neq \Phi\} \quad (1)$$

Where B is the structuring element. The structuring element chosen is 'line'. Region filling makes all the pixels in the bounded regions as white thereby differentiating it from the background. The procedure to fill the region with 1's is

$$Xk=(Xk\text{-}1+B)nA^c \quad (2)$$

Where k=1,2,3…. And B is the symmetric structuring element and X_0=p, where p is the point inside the boundary. Structuring element chosen is 'holes'. Erosion aims at removing the irrelevant details in an image.

With A and B as sets in Z^2, the erosion of A by B is

$$A\text{-}B=\{z\backslash (B)z\ C_A\ \} \quad (3)$$

B is the structuring element. The structuring element chosen is diamond.

3.2 Region Growing Algorithm

Region growing algorithm is an algorithm that appends pixels or sub regions into larger regions based on predefined criteria. Hence the region of interest i.e. the weld defect is obtained directly through similarity detection. The algorithm involves selecting a seed pixel, which is the representative pixel of the region of interest. The seed pixel chosen is that whose intensity is eth median of pixel intensities in the region of interest. All pixels with nearly same intensities are grouped together. Grouping nearly similar pixels is achieved by selecting a threshold value. The selection of similarity criteria is dependent not only on the threshold but also on connectivity. Connectivity when considered prevents meaningless segmentation.

3.3 Euclidean Distance Based Color Image Segmentation

Color is a powerful descriptor that simplifies object identification and extraction from a thermograph. Of the various color models, RGB color model is considered for further processing of the image. In the RGB color model, each color appears in its primary spectral components of red, Green and blue. Each RGB color pixel is a triplet of values namely Red, Green and Blue. Segmentation in color domain is based on similarity detection rather than discontinuity based.

The algorithm involves selecting an estimate of the average color that is to be segmented. Classifying each RGB pixel in the image as having the specified average color or not. I.e. similar pixels are grouped together. Euclidean distance is chosen as the measuring parameter. Let the average pixel chosen be represented as 'a'. Any image pixel 'z' is said to be similar to 'a' if the Euclidean distance between them is less than a specified threshold D_0. Choosing D_0 is dependent on the defect that is to be classified. For all the thermographs of same defect, the value of D_0 is same, hence making this algorithm image independent and parameter independent. The Euclidean distance between 'z' and 'a' is

$$D(z,a)=[(z_R-a_R)^2+(z_G-a_G)^2+(z_B-a_B)^2]^{1/2} \quad (4)$$

Where the subscripts R,G and B denote the RGB components of vector 'a' and 'z'. The extracted defects are then described quantitatively using feature vectors. The feature vectors used for description are major axis length, minor axis length and area.

4. RESULTS AND DISCUSSION

The hotspot isolated thermographs for three different depths of Penetration through conventional algorithm; region growing algorithm and Euclidean distance based color image segmentation are as shown in Fig. 4, Fig.5 and Fig. 6. respectively.

The performance of these algorithms in terms of accuracy, time consumption, parameter dependency and image specificity are compared in Table 1.

From the table it is clear that the area, major axis length and minor axis length are nearly same. Choosing suitable threshold and average pixels in region growing and color segmentation algorithms can further reduce the deviation. The conventional algorithm is strongly dependent on the parameters namely filter and size of the filter chosen for edge detection, structuring elements and its size chosen for morphological processing. Hence these algorithms cannot be standardized fro a particular defect. Different programs (with different structuring elements) are to be written for images even of same defect.

Region growing and Euclidean algorithms require standard parameters for all the images of same defect. These algorithms can be standardized and can be considered for on-line weld monitoring. However the time taken by Euclidean algorithm is more when compared to region growing.

5. CONCLUSION AND FUTURE WORK

All the three algorithms are effective in hotspot identification and quantification. However due to its parameter dependency and different programs for different images of the same defect conventional algorithm is not suited fro on-line weld monitoring. Though region growing and Euclidean distance based algorithm can be standardized for a defect, due to less time consumption the Region Growing algorithm is best suited for on-line weld monitoring.

Wavelet based algorithm may also be considered due to its multiresolution analysis may detect more number of defects on a thermograph. But time taken by this algorithm will be more than any of the developed image processing algorithms.

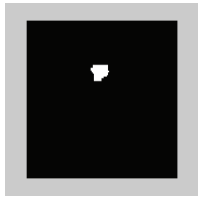


Figure 4a (100% depth)

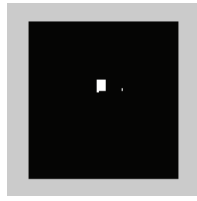


Figure 4b (80% depth)

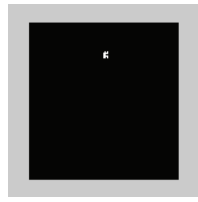


Figure 4c (60% depth)

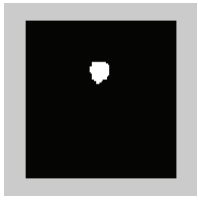


Figure 5a (100% depth)

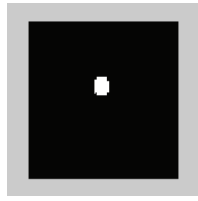


Figure 5b (80% depth)

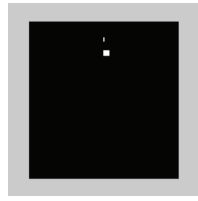


Figure 6c (60% depth)

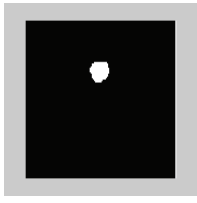


Figure 6a (100% depth)

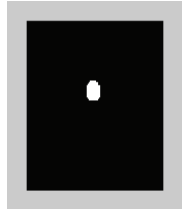


Figure 6b (80% depth)

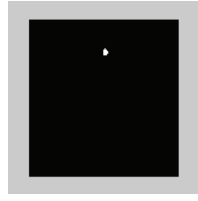


Table 1 Performance Evaluation of Algorithms (Comparison)

Parameters/Algorithm		Conventional			Region Growing			Euclidean Color		
Accuracy of Result	Depth/ Feature Vector	100%	80%	60%	100%	80%	60%	100%	80%	60%
	Major Axis Length (in cm.)	0.4879	0.2948	0.1732	0.4245	0.3169	0.1579	0.528	0.418	0.126
	Minor Axis Length (in cm.)	0.3463	0.2731	0.1385	0.3258	0.3039	0.1325	0.432	0.409	0.110
	Area (in sq. cm)	0.1242	0.0594	0.018	0.1053	0.0738	0.0153	0.176	0.133	0.009
Time Taken (Pentium IV, 2.4GHZ processor)	Time taken for execution (Seconds)	0.4840	0.6250	0.7040	0.2970	0.2810	0.3100	0.4060	0.4690	0.4530
Parameter Dependency	Image Segmentation	Sobel filter Threshold = graythreshold *0.35	Sobel filter Threshold = graythreshold *0.15	Sobel filter Threshold = graythreshold *0.15	Seed pixel, intensity=0.98 Threshold =0.04			Average pixel intensity (R=0.9785, G=0.9785, B=0.9785)		
	Dilation	Line (2 pixels)	line (1 pixel)	No dilation	-	-	-	-	-	-
	Region filling	holes	holes	holes	-	-	-	-	-	-
	Erosion	Square Size = 4 Done once	Square Size = 4 Done twice	Square Size = 2 three times	-	-	-	-	-	-

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DEVELOPMENT AND INTEGRATION OF INTELLIGENT, VOICE STRESS ANALYSIS AND IRIS RECOGNITION TECHNOLOGIES IN CONSTRUCTION

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ABSTRACT

Intelligent systems (neural networks, expert, knowledge, decision support and other systems) in construction can be used on the national, organization and project levels. However, most of all neural networks, knowledge, decision support and expert systems are seeking to find how to make the most economic construction decisions, and most of all these decisions are intended only for economic objectives. Also currently voice stress analysis, digital physiognomy and IRIS recognition technologies are very seldom used in construction. Development and integration of some intelligent, voice stress analysis and IRIS recognition technologies in construction by Vilnius Gediminas Technical University since 1984 are described in the paper.

KEYWORDS

Intelligent, Voice Stress Analysis and IRIS Recognition Technologies, Construction, Development and Integration.

1. INTRODUCTION

Construction intelligent systems can be used on the national [5, 16, 17], organization [5] and project [1, 3, 4, 6, 18, 19] levels.

On the *national* level intelligent technologies enables one to find and analize the required data quickly and from various perspectives, as well as allowing effective communication between interested parties for making important decisions at a distance. Intelligent technologies at country or European levels have been analyzed and written about in a variety of research literature.

On the *organizational* level intelligent technologies are used to get and process the data on financing and investment possibilities as well as on real estate (GIS – Geographical Information System), government-provided services, producers and their products (intelligent electronic catalogues), etc. For example, organizations get the possibility to search for most suitable suppliers, contractors and use market offers for the best advantage. Intelligent technologies also provide the opportunities for learning and qualification improvement (by distance learning, the availability of intelligent electronic libraries).

On the *project* level the use of intelligent systems (i.e. expert, decision-support systems, etc.) allows all the interested parties, (i.e. designers, economists, architects, builders, facilities management personel) to solve the problems concerning the life time of a building (including brief, design, construction, maintenance, facilities management and demolishing stages). For this purpose data bases are being created embracing the data and knowledge obtained from the previously made similar projects as well as the experience of experts and the data contained in various norms, standards and other sources of information.

However, most of all neural networks, decision support and expert systems are seeking to find how to make the most economic construction decisions, and most of all these decisions are intended only for economic objectives. Quite a number of decision making methods (including all multiple criteria decision making methods) may make integrated analyses of many indicators of different dimensions. However, for various reasons they are not made by many computer systems developed in the construction branch. Also currently voice stress analysis, digital physiognomy and IRIS recognition technologies are quite seldom used in construction. Above partly in construction missing technologies have been applied by authors with their associates.

2. WEB-BASED INTELLIGENT, VOICE STRESS ANALYSIS AND IRIS RECOGNITION SYSTEMS

Web-based intelligent, voice stress analysis and IRIS recognition systems in construction developed by authors in cooperation with their associates are as follows:

- Building's Refurbishment Knowledge and Device Based Decision Support System [9, 10, 20, 25],
- Innovation Multiple Criteria Decision Support Web-Based System [26],
- Multiple Criteria On-Line International Trade Decision Support System [7, 26],
- Multiple Criteria Decision Support Web-Based System for Facilities Management [7],
- Cooperative Integrated Web-based Negotiation Decision Support System for Real Estate [12, 13],
- Multiple Criteria Decision Support On-Line System for Construction Products [8],
- Sustainable Development Analysis Web-Based System [26],
- Intelligent Library and Tutoring System [15],
- Voice Stress Analysis System [13],
- IRIS Recognition System [13]
- Ethical Multiple Criteria Decision Support Web-Based System [11],
- Building Life Cycle Decision Support System [2, 22, 23, 24],
- Loan Analysis Decision Support System [21],
- Foundations Analysis Decision Support System [22, 24],
- Buildings' Multivariant Design and Multiple Criteria Analysis Decision Support System [22, 24], etc.

Then the brief study of authors with their associates some of above developed voice stress analysis and IRIS recognition systems follows.

3. PRACTICAL APPLICATIONS OF VOICE STRESS ANALYSER SUBSYSTEMS

The Voice Stress Analyser (VSA) Subsystem measures stress in a human voice. VSA Subsystem can be used for analysis of different situations in construction (work of brokers, analysis of stakeholders' subjective opinions about pollution and health effects, e-learning, etc.). Statistical information database was developed in order to efficiently use VSA Subsystem in practice.

The practical application of the VSA Subsystems in sales of real estate and e-learning are briefly analyzed as follows.

3.1 VSA Subsystem in Sales of Real Estate

A typical situation of a first visit to an apartment was selected. The discussion between the seller and the broker inspecting an apartment for sale was recorded (consent from both). Standard questions were asked during the conversation. Advantages and disadvantages of an apartment were detected, the sales price established, as well as the size of the broker's commission and negotiations on conclusion of a mediation agreement. The VSA Subsystem analyses record shows the vibration curve of a sound document, which indicates the sound frequency in real time. If a sound frequency is high, the oscillation of the sound curve is denser. Such density of oscillations of a sound curve shows that a person is not sure of the correctness of his/her statement or conceals some truth. For example, it was noticed that a

sound vibration curve typically is very dense when a client speaks about the brokering contract. Evidence provided by the VSA Subsystem can show whether a client's statement is false or doubtful.

The research determined that people are usually unsure or conceal part of truth when speaking about brokering contract, exact floor area of an apartment, furniture for sale with the apartment, sale's price of the apartment, and remuneration to a broker, etc. All these criteria are essential in the activities of a broker. False information may leave a broker without remuneration for the work. Knowledge that a client is lying when he/she speaks about such things can also protect a broker against fraud. Currently, when sufficient statistical information is not available yet, it would be wrong to rely on evidence provided only by the VSA Subsystem. However, it can help to avoid a number of misunderstandings and other problems.

A company can use the VSA Subsystem for its specific purposes, e.g. at conferences, during reports to a top manager and at other meetings. Thus the head of a company will have an opportunity to analyse the information, requests and opinions, etc. provided at a meeting and to make decisions on the basis of the evidence of the VSA Subsystem as well as the manager's logical thinking. Such application of the system would not be difficult, because internal regulations of a company allow a head to collect and use information about the company's personnel. Besides, the obtained information would help to meet client's needs and the company's employee's needs in better ways.

As example, a relationship between the deviation from the real area of apartment deliberately increased by the seller (in per cent) and the average microtremor frequency of the voice when claiming bigger floor area is presented in Figure 1. The x-axis shows the deviation (in per cent) of the increased area of the apartment (compared to the real) specified by the seller during the conversation. The y-axis shows the scale of the average microtremor frequency noticed in the seller's voice during the conversation. Besides, the Figure 1 clearly shows the relationship between the level of untruth told by the seller and the average microtremor frequency. The higher the average microtremor frequency the more area is added to the real area of an apartment.

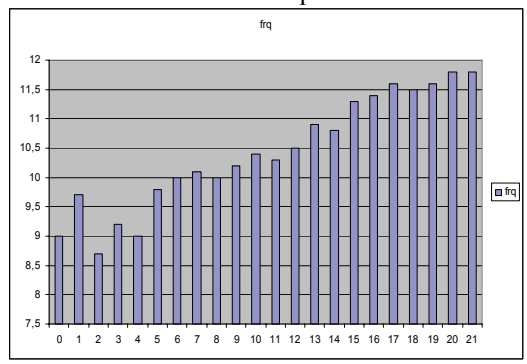


Figure 1 The Relationship Between the Deviation from the Real Area of Apartment Deliberately Increased by the Seller (in per cent) and the Average Microtremor Frequency of the Voice when Claiming Bigger Floor Area

In the nearest future there will be a possibility to assess correctness of provided information (in %) automatically by using VSA Subsystem on the basis of accumulated historic statistical data and determined regression equations. For example, according to a seller's answer about the floor area of an apartment, the VSA Subsystem would automatically convert the answer into frequency and specify the actual floor area of an apartment and the percentage of deviation from the floor area of the apartment as specified by a buyer.

3.2 VSA Subsystem in e-Learning

The research aim was to compare data received during an examination with ILTS-BP (information on correct and incorrect answers, time periods for each question, and the number of times a student changed an answer to each question of a test) with similar data received from the Voice Stress Analyser (VSA) Subsystem, to make practical conclusions and to plan future research. This research helped to determine changes of students' psychophysical conditions during examination. During an e-test, students were asked to select one correct answer from the provided alternatives and to say the answer aloud. The sound record of each answer was then saved into a PC memory with an identification code for listening and further analysis. Records were analysed by using the VSA Subsystem and the frequency range of micro-tremors for each specific answer to an e-test question was determined. The higher frequency of

voice vibrations was determined when analysing voice answers to "unknown/difficult" questions. It was found that the emotional stress of a student was higher when answering "unknown/difficult" questions.

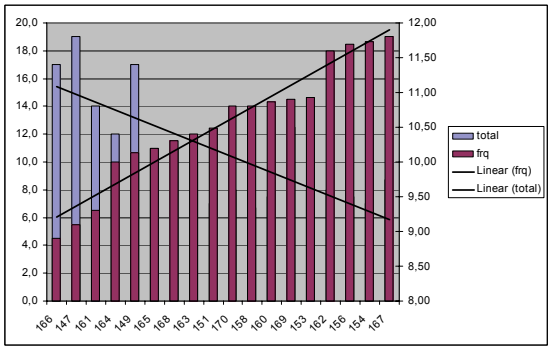


Figure 2 Correlation of Relationships Between Emotional Stress and Correct/Incorrect Answers to an e-Test

The reliability of the results was assessed by making a correlation analysis of emotional stress and of evaluations of correct/incorrect answers to test questions. The analysis showed that a correlation exists between emotional stress and the correctness of an answer. During the experiment, a total of 4,000 voice records in four student groups were examined and analysed. The research helped to determine whether questions can be classified (in respect to students) as "known/simple", "unknown/difficult" and remaining questions in-between these two groups. The "unknown/difficult" experienced higher than average emotional stress, and zero or minor emotional stress when answering "known/simple" questions. On analysis of the whole set of answers, a direct relationship was noticed between emotional stress and correct/incorrect answers to an e-test, i.e. answers to "unknown/difficult" questions scored less than answers to "known/simple" questions (see Fig. 2). During the research, the average microtremor was calculated for each question. Part of the results is shown in Figure 2.

Figure 2 shows the relation between a student's grade and the average microtremor frequency of the answers to test questions. The x-axis shows ID numbers of students who were passing the examination. During examination students had to mark and to say aloud the right answers to 20 questions within 10 minutes. The left side of the y-axis shows the scale of points received by each student. A student who correctly answered all questions could get a maximum of 20 points. The right side of the y-axis shows the average microtremor frequency of each student during the examination. Besides, the Figure 2 shows two correlating curves obtained during the research; they show the direct relationship between the grade and the average microtremor frequency. For instance, the higher is the average microtremor frequency the worse is the grade. And vice versa.

As seen from the data in Fig. 2, a student can be assessed according to the regression relationship between emotional stress and correct/incorrect answers to e-tests. On the development of a more exhaustive database of voice analysis such evaluations will become more precise. For example, when a teacher gives a student such questions as "Are you well-prepared for the exam?, What mark would you give to your knowledge?, and Have you learnt everything?" before an examination, the VSA Subsystem determines the average micro-tremor of the answers, and the student can be assessed precisely by being given a mark.

In the future there will be a possibility to assess students' knowledge automatically by using VSA Subsystem on the basis of accumulated historic data and determined regression equation. For example, the VSA Subsystem will automatically assess a student's knowledge during an examination according to the student's spoken/oral answers, i.e. the VSA Subsystem will convert student's answers into Hz and the IITS will show a mark according to the amount of Hz. solutions.

4. IRIS RECOGNITION TECHNOLOGIES IN E-LEARNING

An IRIS Recognition Subsystem using the analogy of the Voice Stress Analyser Subsystem is being developed. Similarly to the Voice Stress Analyser Subsystem, the IRIS recognition technology can show the relation between changes of the eye's pupil and the emotional condition of a person. The IRIS Recognition Subsystem uses technology to identify features particular to each student's eye. The IRIS Recognition Subsystem is technology for the measurement of human physiological or

behavioural features. Current research is searching for a relationship between the change of an iris' diameter and the emotional condition. During research, a micro-camera is mounted in front of a student; the camera records changes of the diameter of the student's iris and passes the data to a PC. Special software takes pictures of the iris every three seconds and saves the results into a PC's hard-drive in separate files. By using the *Matlab* software and accessory scripts, the diameter of the iris is calculated by using the pictures, and the determined changes are saved into a database. For a final result, a database which keeps students' answers to questions and the information about change of the diameter of the iris during examination (every three seconds) was developed.

A student can be assessed according to the regression relationship between emotional stress and correct/incorrect answers to e-tests. On the development of a more exhaustive database of IRIS Recognition such evaluations will become more precise. For example, when a teacher gives a student such questions as "Are you well-prepared for the exam?, What mark would you give to your knowledge?, and Have you learnt everything?" before an examination, the IRIS Recognition Subsystem will automatically assess the student's knowledge according to the average number of changes in the student's iris and on the basis of the accumulated data and determined causal relationships. In the future there will be a possibility to assess students' knowledge automatically by using IRIS Recognition Subsystem on the basis of accumulated historic data and determined regression equation.

5. CONCLUSIONS

Since 1984 various intelligent, voice stress analysis and IRIS recognition (Building's Refurbishment, Innovation, International Trade Decision, Facilities Management, Real Estate, Construction Products, Sustainable Development, Intelligent Library and Tutoring System, Voice Stress Analysis, IRIS Recognition, Air Pollution and Health Impact, Ethical, Building Life Cycle, Loan, Foundations, Buildings' Multivariant Design and Multiple Criteria Analysis, etc.) systems in construction developed by authors in cooperation with their associates in Vilnius Gediminas Technical University.

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SVD BASED ALGORITHMS FOR ROBUST FACE AND OBJECT RECOGNITION IN ROBOT VISION APPLICATIONS

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ABSTRACT

Contemporary society is highly networked and thus biometrics based surveillance has paramount importance for various security based reasons. The automatic, remote and robot vision based system are being deployed in a large way [11, 12]. The success of these schemes is highly dependent on robust algorithms for both face and object recognition. In this paper, we propose a very robust approach to face/object recognition based on Singular Value Decomposition (SVD). We first provide technical reasons to substantiate the claims made by T.Yuan et al [1], then we provide appropriate reasons for the robust behavior of SVD and finally, we corroborate the proposed concepts through extensive experiments on two standard databases which includes face and objects under both clean and noise conditions.

KEYWORDS

Face Recognition, Object Recognition, Singular Value Decomposition, Principal Component Analysis (PCA), Fisher Linear Discriminant, Analysis (FLD), Noise Analysis

1. INTRODUCTION

Among various biometric traits such as speech, fingerprint, handwriting, face recognition etc. there is tremendous attention on face recognition due to its technical challenges and potential applications. This area has roots which dates back to last four decades and is still a growing area in robot vision research [2]. It has many potential applications such as biometrics, surveillance systems, content based video retrieval systems, antique verification and face image transmissions. Nevertheless, there are still many challenging problems such as recognition under different noisy conditions, occlusions, illumination and/or pose variations.

There are two main approaches to face recognition. The first approach is feature based matching using the relationship between facial features such as eyes, nose and mouth [3, 4]. The second approach is template matching using the holistic features of the face images[4, 7, 8, 9].

Many successful methods have been proposed using holistic features of the faces and one popular category is based on Singular Value Decomposition (SVD) for face recognition [5, 6, 7, 8]. Hong [5] has proposed a SVD based recognition method which uses the singular values (SV) as the feature vectors.

The effectiveness of SVD has been tested in [5] and [6]. In [5], an error rate of 42.47% was

recorded which was thought to be caused by the statistical limitations of the small samples. Cheng [6] proposed a human face recognition method based on the statistical model of small sample size that also used the SV's as the face features, where a good discrimination ability was obtained with an accuracy rate of 100%. This accuracy is obtained on a moderate size face database and its performance on a larger database is unclear. In [7], a new face recognition method based on SVD was proposed by using reconstruction error on singular values of different face images and data fusion method. It was reported that the recognition accuracy of this method reaches 96% on the ORL face database. Furthermore, D.Zhang et.al. [8] have proposed a method based on SVD and conventional PCA [9] to improve the classification performance of the latter method under the condition when the face database contains only one image for training. This situation is called single sample per person problem which has evinced more importance in the current face recognition technology.

Recently a paper was proposed by T.Yuan et.al [1], in which, unlike the claims made by the aforementioned papers, they have claimed that the SVs contain little useful information for face recognition and most important information is encoded in the two orthogonal matrices of the SVD. They have ascertained their claims through simple demonstration and no supporting theory was provided to affirm their claims. Moreover, the reasons for the efficiency and robustness of SVD under various noise conditions (modelled by different distributions) are still not being proclaimed in the literature of face recognition community. In our work we address this issue by providing convincing reason.

The three essential contributions of our work are: (i) Providing technical reasoning to substantiate the claims made by T.Yuan et.al [1]. (ii) Providing appropriate reasons for the efficacy and robust behavior of orthogonal projections of SVD. (iii) Performance evaluation for comparing the results of SVD with the eigen vectors of the covariance matrix under both noisy as well the clean conditions.

The rest of the paper is organized as follows: In section 2, we briefly outline the algorithm of SVD. The experimental results and analysis are given in section 3. The conclusions are drawn in section 4.

2. SINGULAR VALUE DECOMPOSITION

The singular value decomposition (SVD) is one of the most important tools of numerical signal processing. It is employed in a variety of signal processing applications, such as spectrum analysis, filter design, system identification etc.

The theory of SVD states that any matrix A of size m× n can be factorized into a product of unitary matrices and a diagonal matrix, as the following:

$$A = U \sum V^T \tag{1}$$

where $U \in \Re^{m \times m}$ is unitary, $V \in \Re^{n \times n}$ is unitary, and $\sum \in \Re^{m \times n}$ has the form $\sum = diag\left(\alpha_1, \alpha_2, \ldots \alpha_p\right)$, where p is the minimum value of m or n. The diagonal elements of $\sum$ are called the singular values of A and are usually ordered in descending manner.

We use the orthogonal matrix U as the projection vectors (instead of eigen vectors of covariance matrix) for feature extraction while implementing Eigenface [9] and Fisherface [10] methods. In all our discussions, we call these methods as PCA+SVD and FLD+SVD respectively. In contrast to eigenvector calculations involved in conventional algorithms, the SVD has several advantages: (i) computationally efficient and (ii) it is robust under noise conditions.

The SVD are known to be more robust than usual Eigen vectors of covariance matrix. This is because, the robustness are determined by the directional vectors rather than mere scalar quantity like magnitudes (Singular values stored in $\sum$). Since U and V matrices are inherently orthogonal in nature, these directions are encoded in U and V matrices. This is unlike the Eigenvectors which need not be orthogonal. Hence, a small perturbations like noise (in case of images or signals) have very little effect to disturb the orthogonal properties encoded in the U and V matrices. This we believe could be the main reason

for the robust behavior of the SVD. This also affirms the claims made by T.Yuan et al [1].

3. EXPERIMENTAL RESULTS

In this section, we conduct several tests to affirm the proposed claims. Robot vision applications encounter most frequently face and object recogni tion tasks generally under noisy environment. For this purpose we have used two standard dabases namely ORL face database[1] and COIL-20 object database[2]. In all our experiments, the nearest neighbor classifier (Euclidean distance) is used for classification purpose and the number of projection vectors (k) is controlled by the following equation:

$$\frac{\sum_{i=1}^{k}\lambda_i}{\sum_{i=1}^{N}\lambda_i} \geq \theta \qquad (2)$$

Where λ_i are eigen values such that $\lambda_1 \geq \lambda_2 \geq \lambda_3 \ldots \geq \lambda_N$, N is the total number of eigen values, k is any scalar value and θ is a preset threshold. In most of our experiments, θ is set to 0.98 to select the value of k. We call this as *confidence interval* throughout the paper. Finally, all our experiments are carried out on a P4 3GHz CPU and 1GB RAM memory on Matlab 7 platform.

3.1. RESULTS ON ORL DATABASE

The ORL database contains 400 images corresponding to 40 different persons with each person having ten different views. The variations include changes in expression, facial details and slight variations in pose. Few example images are shown in Fig.1. On this database, we have evaluated the performance of algorithms under two test conditions: 1) Performance under clean or noise free conditions, i.e. when both sample size and pose are varied and 2) Rigorous experiments under different noisy conditions modeled by five various distributions: Uniform (for Salt-and-Pepper behavior), Gaussian, Weibull, Exponential and Beta.

First, an experiment was performed using first five samples per person for training and the remaining images are used for testing. So effectively, 200 (40 × 5 = 200) images were constituted in both training and testing sets. Table 1 gives the comparison of PCA based methods on recognition accuracy[3], corresponding dimension of the feature set and running time for 98% confidence interval. It is clear from the table that the SVD based PCA and FLD methods outperformed their conventional counterpart algorithms interms of recognition accuracy and running time costs.



Figure 1 Few Sample Images from ORL Database

Table 1 Comparing Methods for Five Training Samples (98% Confidence Interval)

Methods	Accuracy (%)	Dimension	Time (secs)
PCA [9]	92.00	151	25.77
PCA+SVD	94.00	187	17.89
FLD [10]	83.50	149	36.98
FLD+SVD	86.25	187	29.33

The issue of noise modeling is crucial to check the robust behavior of the algorithm under real time pattern recognition and computer vision tasks. In our work, we have modeled five noise environments using different continuous distributions and used them in their descretized version[4]

[1] http://www.uk.research.att.com/facedatabase.html

[2] www1.cs.columbia.edu/CAVE/research/softlib/ coil-20.html

[3] Recognition accuracy is defined as the ratio of correctly classified images to the total number of test samples

[4] Matlab command imnoise is used to add salt-and pepper effect. Control parameters μ and _ are fixed to 0 and 0.5 respectively for Gaussian noise, the _ value is fixed to 1 while creating exponential noise, K and _ are fixed to 0.5 and 2 to generate weibull noise and both _ and _ values are fixed to 0.5 to create the beta noise, in their respective distributions

We selected first image from each class and generated 10 noise images by varying the noise density from 0.1, 0.2, . . . , 1.0. Likewise, 50 noise images are created for each class corresponding to 5 different distributions. Since ORL contains 40 classes, 2000 noisy images are created, which we use as test samples. First five clean samples from each class of ORL are used as training samples. Table 2 presents the average recognition accuracy (average of ten different noise densities) obtained by various algorithm. Again it can be ascertained that the SVD based algorithms remained robust for all the noise conditions.

Table 2 Performance Comparison for Different Noise Conditions for 98% Confidence Intervals

Noise Conditions	Methods			
	PCA	PCA + SVD	FLD	FLD + SVD
Gaussian	96.75	98.50	89.25	90.00
Salt-and-Pepper	63.75	64.75	58.50	60.75
Exponential	79.00	82.50	75.75	79.75
Weibull	67.00	73.50	64.25	71.00
Beta	100	100	98.50	99.00

3.2. RESULTS ON COIL-20 DATABASE

This database contains 1440 grayscale image of 20 objects. The objects are placed on a motorized turntable against a black background. The turn table was rotated through 360 degrees to vary object pose with respect to fixed camera. Images of the objects were taken at pose interval of 5 degrees, which correspond to 72 images per object. The sample views of twenty objects considered in this database are shown in Fig.2

We conducted an experiment on this database by varying the number of training samples for 98% confidence interval. This result is shown in Table 3. It can be seen that the SVD based algorithms outperformed their counterparts. These results endorse the applicability of the SVD based algorithms for object recognition.



Figure 2 Few Sample Images from COIL-20 Database

Table 3 Recognition Accuracy (%) for Varying Number of Training Samples (98% Confidence Intervals)

Noise Conditions	Number of Training Samples			
	18	24	36	48
PCA	75.97	82.70	90.48	93.33
PCA+SVD	77.15	84.51	91.52	94.44
FLD	67.63	72.77	81.73	88.75
FLD+SVD	72.91	78.81	87.01	91.94

4. CONCLUSION

In this paper we have proposed SVD based algorithms for robust face/object recognition. We have ascertained the efficacy of the SVD based algorithms for both face and object recognition which are useful in later robot vision related tasks. We have conducted experiments under both clean and noise conditions. For later case, we have modeled five different noise conditions using continuous distributions and used them in their descretized version. Overall, we observed SVD based algorithm performing significantly better than conventional algorithms which use covariance matrix construction and subsequent Eigen value decompositions.

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MANAGEMENT
AND
PRODUCTION ASPECTS

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AUTOMATION IN SITE MANAGEMENT: A QUALITATIVE APPROACH

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ABSTRACT

This paper will address a new approach to construction management: Qualitative Construction Site Assessment System (QCSAS). QCSAS is essentially a site management software package. The objective of this system is three fold. Firstly, it aims to provide a holistic view of construction site to the project manager. It tries to achieve this by tracking essential factors like construction progress, construction quality, safety on site and resource requirement. Secondly, it assesses the condition of all factors on site in qualitative terms by using *fuzzy logic*. Thirdly, the system intends to achieve smooth information flow between various participants of site, i.e., the site supervisors, procurement officer, quality inspector, safety engineer, planning engineer and project manager with minimal effort and time wastage.

KEYWORDS

Construction Planning and Management, Information Technology, Site Management

1. INTRODUCTION

In early 1990's Information Communication Technology (ICT) has shown increasing importance for its possible applications in construction industry [1]. Complex systems have been developed to cater to the need of efficient planning and management of construction site. Systems involving visual techniques to obtain a bird's eye view of the construction site as the construction progresses have also been developed [2]. They are known as 4D dynamic construction management systems, which show development of site in 3 dimensions with respect to the 'fourth dimension', that is, the time. This aids the planning engineers by giving them better understanding of resource requirement and improves space utilization.

Several Knowledge Based Expert Systems (KBES) have also been developed for improved construction planning management. Systems such as 'Construction Planex', 'GHOST', 'SIPE', 'CONSCHED' and 'HISCHED' are briefly discussed in [3]. Most of these systems (with exception of 'Construction Planex' which deals with work and labor assignment) focus on scheduling. Reference [3] also discusses development of a KBES system for creating a productivity-adjusted schedule. However, in India, the primary tool used for construction planning and management remains MS Excel and MS Project [4]. Some leading construction firms in the country, such as M/s. Larsen and Toubro are using in-house custom-made software packages. But these do not cater to the actual *management* of construction site. They are used for centralized billing and inventory management.

Delays in construction and poor construction quality are problems that are regularly faced by construction industry in India. No study for delays in construction projects in India were found but the figures should be similar to that found by Ayman and Al-Momani in their study of public projects in Jordan, if not worse [5]. They found that out of

130 surveyed projects, 106 had run into delays. Out of these 52 projects were delayed because of change of orders, weather and site conditions. Other reasons should one way or other relate to some sort of mismanagement on construction sites. Thus there is a need for a construction management system that can help project managers fight these delays without compromise on quality and safety standards.

1.1 Failure of Previous Attempts

The concern to be addressed is that such systems have either not been developed or if they have been, the industry isn't using them. It is possible that certain hindrances such as fragmentation in construction sector, lack of computer and trained professionals, security concerns, legal implications are keeping the industry at bay when it comes to using ICT for project management [6]. After having discussions with site engineers, it is our belief that the application of systems have mainly failed because of following factors: (i) Complicated software packages require substantial employee training time (ii) Systems are black boxes and their recommendations (if any) are considered with a certain degree of distrust (iii) Lack of faith that machines can adapt and provide right advise for situations in a highly dynamic system like construction sites (iv) Cumbersome data input with little utility gained without using the advanced features

1.2 Requirements of Practically Applicable Construction Management System

Thus there is a need to develop a system that is easy to give inputs to, utilizes minimal time to give those inputs, can cater to interdependencies, is flexible and finally can manage both "hard" and "soft" data. Most importantly its reports must be easily understandable and useable [7,8].

Now it has been proposed that a force metaphor can be used to describe the comparison between planning versus actual construction progress [9]. A construction project is like a rolling ball on a curved plane. The actual path will depend on the curvature of the curve it rolls on. The curved plane may be defined by various constraints (predicted and unforeseen) on the construction site. Since there will always be unforeseen constraints, the actual path of construction progress can never be accurately predicted. Thus, the difference between the planned project schedule and actual construction progress is observed. This then brings an interesting corollary to our notice. If the actual progress cannot be predicted more accurately, then the emphasis should be more on improving monitoring of construction activities than on improving already existing advanced and fairly acceptable scheduling techniques.

There are several previous attempts at developing better models for construction planning and management. These include models that cater to monitoring dependence relationships, planned/actual construction activities, revision of plans and tracking actual schedule [10]. These features are without doubt important for monitoring construction activities.

Various recommendations have been made through other models. Use of independent interfaces has been strongly advocated [11]. Also, it is advised that systems should work in three different layers:" Tactical layer" (the strategic core of the system), "Operational layer" (where the simulation takes place and results are compiled) and finally "Interface layer" (where the results are displayed and inputs are taken) [12].

A certain phenomenon of *dilution* in information has been noted on site. This dilution is of two types and for the sake of convenience can be termed as "forced dilution" and "natural dilution". Natural dilution in information occurs when information is passed up the hierarchy and small aberrations aren't reported at the top level as a result of averaging out various factors while moving up. Forced dilution occurs due to poor communication between senior management and site engineers. It can be either because of intent to conceal information or because a subordinate decides that the information is not worth bothering his senior about. While *natural dilution* is an acceptable and one might say, even required process in reporting, *forced dilution* may more often result in serious concerns not being informed to the senior managers. A good system should be able to avoid forced dilution but keep natural dilution in reporting.

2. PRESENT STUDY

Keeping in view the discussions in section 1, a fresh approach was adopted for creating a practically applicable system. After some discussions with site engineers, it became clear that there are certain practices that engineers on site are averse to. Engineers need to see the consequence and ultimate value addition of any practice they are asked to do. Also, the system should be simple to use and should require minimum training. To tackle this, it was decided that the site management system should be qualitative in nature rather than quantitative.

Human communication is essentially qualitative in nature. Ironically, in a lot of cases qualitative phrases are more accurate way of passing information than quantitative figures. For example, saying that the quality of formwork is "good" gives immediate and correct understanding of what is intended to be communicated. In contrast, saying that quality of formwork is "7 out of 10" is not only abstract, but also requires significant amount of work by an organization to develop standards in figures for them to be interpreted. Thus, forcing qualitative entities to be dealt with in a quantitative manner creates a redundant cycle as shown in Figure 1 below.

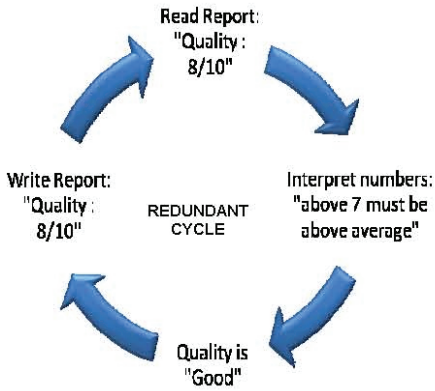


Figure 1 Redundant Cycle of Communication

This cycle brings forth another realization that not only should the data inputs be qualitative (because that's how humans communicate) but the reports should also be qualitative. By making the input and output of the system in qualitative terms, the problem of time wasted on initial training and readability of reports would have simultaneously been addressed.

In addition, the time for data input should be as less as possible so that the site engineers can focus on getting work done. The reports for construction progress should be in real time and similar to time-impact analysis. That is to say that two parallel construction schedules will be maintained. One will track the current progress of schedule and adjust itself accordingly. Using this schedule, the project manager can track delays in actual project and shift in critical path (if any). The other schedule will remain same as the original and will show which activities have exceeded their assigned time. The system should be entirely flexible and should allow changes at "operational layer", thus allowing user to set standards that he wishes to follow at the construction site. Finally, it should produce an "easy to navigate" and readable report of the entire construction site. In final reporting it should be able to avoid *forced dilution* in information so that there isn't any loss of important information but *natural dilution* is allowed to occur so that not every small problem on the site has a serious effect on the overall report.

3. OVERVIEW OF THE SYSTEM

The QCSAS system works with two modules running in parallel and in co-ordination with each other [13]. One system deals with critical path and scheduling of activities. The other deals with the core function of QCSAS, which is to make decisions about the daily conditions of the site. They interact in together to make an effective tool for site management as shown below in Figure 2. There are essentially 6 core members on the site who deal with the QCSAS system. We will refer to them as site officers. They include the project manager, the planning engineer, site supervisors, quality engineer, site safety engineer and inventory in charge/ procurement officer.

To begin with, the planning engineer of the site will develop the initial hierarchical model for the construction site. He will also submit the pre-decided list of activities with their optimum times and quantities. Once he does that, the system will generate the original critical path. This stage of work on QCSAS will be referred to as the initialization stage. The system recognizes two types of variables: qualitative and quantitative.

Qualitative variables: These variables are all those whose reports can be directly be submitted in linguistic form using fuzzy logic, that is, in words like "good", "bad" or "average". These include construction site quality and construction site safety. Fuzzy logic is used to express all conditions in qualitative terms. This allows engineers on site to easily communicate with the software, thus reducing the cost and effort in training the personnel. For example, it is easier and ironically more accurate for a quality inspector to state that the quality of concreting is "good" instead of stating that the quality of concreting is "7 on a scale of 1 to 10". For example the quality of concreting may have following states: Excellent, Good, Average, Concern and Poor. The quality engineer may input the choice that is appropriate in his judgment. Provision is also provided for giving comments in case the need arises to explain the situation. It is also possible that certain variables are quantitative in nature. For example progress cannot be measured in terms of qualitative expressions. Such data is normalized in by using a pre-defined graph (referred to as a template), a "target" value and a pre-defined equation. For example, let the target be to complete concreting of 15 meters length of first lift of a concrete wall and the template of the standards for construction progress set by the project manager is as shown in Figure 2.

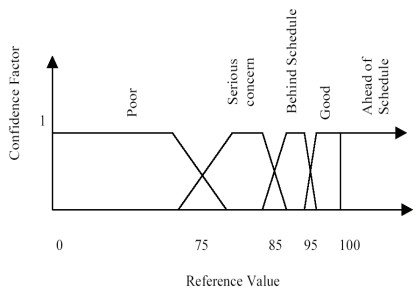


Figure 2 A Sample Template for Setting Standards for Progress

The pre-defined equation for this input module is shown in Eq. 1. If the total target achieved is 13 meters length then the reference value becomes 86.67, which implies that the progress is "Behind Schedule".

$$\text{Reference Value} = \frac{\text{Input Value}}{\text{Target Value}} \times 100 \qquad (1)$$

The templates, target values and the normalization equations will be different for different type of base variables.

Quantitative variables: These variables are those whose inputs can be given in numbers more conveniently. They include resource requirements on site and construction progress

The next stage of the QCSAS is daily processes. The daily process has two sub-sections. The first is '*Updating of the Hierarchical Model'*. Under this section, the site supervisors, quality engineers, safety engineers and procurement officer manage their section of the hierarchical model. They make changes to it by adding new variables that are to be monitored and deleting those that aren't being monitored anymore. The targets for quantitative variables are also updated in this process. This way, the planning engineer doesn't have to bother with keeping track of what all is going on the site and take the pains for updating the entire model. The second sub-section is *'Submitting Daily Reports'*. This involves submitting the status of qualitative variables and values of the quantitative variables. The total process shouldn't take more than 15-20 minutes per site officer daily. As the site supervisors submit the construction progress, QCSAS updates the critical path and saves it as the current critical path. As a result, the project manager should have a compiled report for the previous day within an hour of the beginning of the day. The final stage is the report generation.

4. WORKING OF THE SYSTEM

Some variables are inherently quantitative (i.e., "hard") in nature. These variables include those measuring progress of construction on a site and resource requirements on site. The values are entered in form of numbers and their status is also obtained by comparing the submitted values with pre-decided numerical target values. For example, it may be decided that the target for concreting for a particular day is 40 cubic meters. The value submitted for the concreting achieved that day may be 37 cubic meters. From this it may be concluded that the status of the work is "on time". Thus both the submitted value and the target value for deriving the status of the variable are in numerical form. It is noteworthy that though the variable is dealt with in quantitative terms, the final conclusion is always qualitative in nature, i.e., it is

a human expression and not some mathematical identity.

Meanwhile other variables such as construction safety and construction quality are inherently qualitative (i.e., "soft") in nature. The quality of work will always be described as "good", "bad" or "average". These are already in form of human expression. Thus their submitted value is itself the status of the variable and is always in qualitative terms. More details can be found elsewhere [13]. It is apparent from the above discussion that for us to make sense of status (or condition) of any given variable we must convert it into a qualitative judgment. In further sections, it will be discussed how QCSAS achieves this.

4.1 Hierarchical Model

QCSAS is designed to understand a site in form of hierarchy. All aspects of the construction site are viewed as *variables* by QCSAS. If there is any aspect of construction site whose status is wished to be obtained or monitored by engineers on the construction site, it will be entered into the QCSAS system as a variable.

To begin with, any project manager would like a system like QCSAS to tell him about the overall conditions of the site. Let us say that the "overall condition of the site" is a variable and name it as "Main Report". Now, it is apparent that there are several aspects of the construction site that need to be monitored to actually derive the "overall condition of the site" or the "Main Report". For this purpose we would want to monitor "Construction Progress", "Construction Safety", "Construction Quality" and "Resource Requirements" on the construction site. The model of the construction site is now beginning to take shape of a hierarchy tree as shown in Figure 3 below. These variables may then further have more children as new levels are developed. The hierarchical model will have different levels. The top most level is that of the "Main Report" variable. The construction site can now be further developed by adding more sub-variables and developing new levels.

The existence of variables on the hierarchical model is dynamic in nature. That is to say, that only those variables, which are being monitored, exist on the model tree.

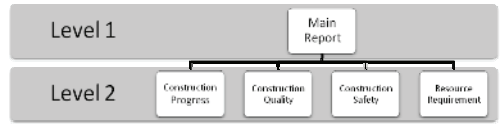


Figure 3 Hierarchical Model of Construction Site

The second level of the *variable tree* is also known as the Parent Tree. This is so because all subsequent variables under this level will have specific nature will be identified with the type of Parent tree under which it exists. For example, all variables under the Parent Tree "construction progress" will be progress type variables and will be concerned with progress of the work on a construction site.

All variables can be classified into two broad categories of variables: parent variable and end variable. The parent variables are the ones that have "children" under them. They have following properties: (i) They have sub-variables or "children" under them. (ii) Their status is derived from combining the status of all its children (iii) They are always qualitative in nature since they represent the combined status of their children (iv) No one need be directly responsible for these variables since they need no direct input from the engineers on the construction site.

The end variables, on the other hand, have the following properties: (i) They have no sub-variables or "children" under them (ii) They can be qualitative or quantitative in nature depending on what type of variable they are (iii) Their status is submitted if they are qualitative in nature or their values are submitted if they are quantitative in nature (iv) They must have someone assigned to them who will be responsible for entering their status or numerical data

5. GENERAL DISCUSSION

The prototype of QCSAS was tested on Delhi Metro Rail Corporation Construction Site under M/s. Larsen and Toubro Ltd. The site planning engineers found the system to be a novel approach towards Information management on site and suggested improvements such as inclusion of a module of making bill of quantities, automatic updating of inventory requirements as per on-going construction work and resource-leveling in critical path.

Since QCSAS, deals in qualitative terms the technical training required for an engineer is minimal. However, the effectiveness of the system depends largely on how motivated the project manager is to imply this system of site assessment. This calls for educating the site officers about the importance of making daily reports for 15-20 minutes. Therefore some level of adjustment is required in cultural and people processes.

6. CLOSING REMARKS

The paper presented development of Qualitative Construction Site Assessment System (QCSAS). The system is based on a qualitative communication on construction site. This is a completely new method of operations in field of information dissemination on a construction site. For any construction industry to adopt QCSAS, they must slightly change their strategic framework for site assessment. The change in strategy should give the project manager more support to use a qualitative system QCSAS for internal assessment of site conditions without interference from higher echelons in the industry.

7. ACKNOWLEDGMENTS

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INFORMATION FUSION FOR MAKING CREDIT DECISION OF PPP ROAD PROJECTS

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ABSTRACT

The systematic aggregation of information is crucial in decision making. If the information is derived from various sources, then the information fusion problem can be transformed into a multi-criteria decision making model. The information fusion problem, thus, is reduced to (a) determining the structure of the hierarchy to be used; (b) computing the degree of satisfaction of criteria based on the observed features; and (c) the nature of the connectives at each node of the hierarchy. The degrees of satisfaction of criteria need to be determined in linguistic terms in case the information is not precise and complete in nature. In view of this, the suitable aggregation operators are the fuzzy connectives. Choquet fuzzy integral is one of the preferred fuzzy connectives for aggregating the information in case there are interactions between the criteria. This paper discusses the application of Choquet fuzzy integral in information fusion with the help of the information the lenders used in making credit decision to Public Private Partnership (PPP) road projects. Lenders to PPP road projects are more concerned with the debt servicing capability of the projects. Lenders aggregate information on the performance of the project with respect to the various aspects, which can influence the debt servicing capability, of the project to assess whether the risk/reward profile of the project match their risk/reward appetite. Information fusion using Choquet fuzzy integral facilitates systematic aggregation of the information and enables the lenders to derive the degree of match between their risk/reward appetite and the risk/reward profile of the project.

KEYWORDS

Public Private Partnerships, Project Finance, Debt Financing, and Information Fusion

1. INTRODUCTION

The importance of systematically aggregating the information for decision making in the construction management perspective requires no further emphasis. A typical decision making problem like making a decision to select a construction firm as the EPC contractor for a project requires aggregation of the information on the various dimensions such as experience, financial strength, managerial and engineering capabilities. The information on these dimensions is derived from diverse sources. Krishnapuram and Lee had suggested that information from various sources can be aggregated in a hierarchical manner with multilevel framework [1]. The node in the hierarchical network can be modelled as criterion and the information aggregation problem can be converted to a multi-criteria decision making model, with the input to the node as degrees of satisfaction of the sub-criteria and the output as the aggregated degree of satisfaction of

the criterion. The information fusion problem can, thus, be reduced to: (a) determining the structure of the hierarchy to be used; (b) computing the degree of satisfaction of criteria based on the observed features; and (c) the nature of the connectives at each node of the hierarchy.

The degrees of satisfaction of the criteria can be determined objectively if the information is precise and accurate in nature. However, if the information is not precise and complete in nature, the degrees of satisfaction of the criteria can best be computed in the form of linguistic terms. Grabisch had classified the appropriate operators available for aggregating linguistic terms into t-norm, t-conorm, and averaging operators [2]. These operators are suitable for aggregating the information when the criteria are linearly independent. When the criteria are not mutually independent, these operators fail to yield accurate results on the aggregated information. Fuzzy integral is reported to be the preferred operator for aggregating the information in case there are interactions between the criteria [3].

Highway projects procured through Public Private Partnership (PPP) route are financed with funding from various funding agencies. Commercial banks have been one of the funding agencies providing major portion of the debt financing to PPP road projects. When debt financing is provided on a Project Finance basis, lenders have limited or no access to the sponsors' assets. Lenders look at the revenue earning potential of the project as the major source for servicing the debt. They are also more concerned with the downside risks associated with the projects that can have adverse effects on the project capacity to service debt [4]. Lenders prior to underwriting the loan undertake a loan approval process wherein the lender's project finance team examines the various aspects of the project, namely technical, commercial, financial, marketing, management factors, sponsor's financial strength and experience, security arrangements, and credit support. The information on these aspects are derived from various sources, including project feasibility study reports, concession agreement, EPC and O&M contracts, shareholders agreement, financial model, and information memorandum [5]. The lenders aggregate information on these aspects to examine whether the risk/reward profile of the project under examination matches their risk/reward appetite. The degree of match influences the lender's decision to advance project finance loan to the project. This paper discusses the application of fuzzy integral in aggregating information for decision making using the information on the various aspects of PPP road projects that the lenders take into account in making the credit decision.

2. FUZZY MEASURE AND FUZZY INTEGRAL

Fuzzy integral is the general term for integral with respect to the fuzzy measure [6]. The concept of fuzzy integral was first put forward by Sugeno, in the early seventies, who considered fuzzy measures and suggested fuzzy integral as a generalization of Lebesgue integrals.

2.1. Fuzzy Measure

Fuzzy measure is a generalization of the notion of measure in mathematical analysis and it relaxes the condition of additivity for the classical measure and only assume monotonocity [7]. There are several classes of fuzzy measures but Sugeno measure is the most commonly used fuzzy measure in human subjective evaluation, pattern recognition, and decision analysis. Computing the Sugeno fuzzy measure is made simpler with the help of the λ rule. The properties of Sugeno fuzzy measure are illustrated below [8, 9].

Let g be a fuzzy measure on a finite set $X = \{x_1, x_2, x_3, \ldots\ldots x_n\}$. The function g such that $g(x_i): x_i \in X \rightarrow [0,1]$ is known as the fuzzy density function. For simplicity, $g(x_i)$ is denoted as g^i. The fuzzy measure, $g_\lambda(A)$, of a finite set, say $A = \{x_1, x_2\} \subset X$, can be obtained from the fuzzy densities as follows:

$$g_\lambda\left(\{x_1, x_2\}\right) = g^1 + g^2 + \lambda g^1 g^2 \qquad (1)$$

and, generally

$$g_\lambda\left(\left\{x_{i_1}\cdots x_{i_m}\right\}\right)=\sum_{j=1}^{m}g^{i_j}+\lambda\sum_{j=1}^{m-1}\sum_{k=j+1}^{m}g^{i_k}+\cdots$$
$$\cdots+\lambda^{m-1}g^{i_1}\cdots g^{i_m}$$
$$=\left[\prod_{x_i\in A}\left(1+\lambda g^i\right)-1\right]\Big/\lambda,\quad \lambda\neq 0 \qquad (2)$$

We know that the fuzzy measure of the finite set $X=\{x_1, x_2, \ldots..x_n\}$ is equal to one and, then, Equation 2 reduces to Equation 3.

$$\lambda+1=\prod_{i=1}^{n}\left(1+\lambda g^i\right) \qquad (3)$$

If we denote the right hand side as $G(\lambda)$, then the solutions to the above equation are the intersections between the polynomial $G(\lambda)$ and $\lambda + 1$.

If all the fuzzy densities g^i, $i = 1, 2, 3\ldots..n$, are known then, using the above equation, fuzzy measure of any set A, where $A \subset X$, can be computed. For the information fusion problem, we interpret the fuzzy density value g^i as the grade of importance of some source x_i, towards the final evaluation. The g_λ fuzzy measure of an arbitrary set $\boldsymbol{A}$ represents the importance grade of the set of sources denoted by $\boldsymbol{A}$ towards final decision.

2.2. Fuzzy Integral

Different classes of fuzzy integral had been introduced since the introduction of the concept of Sugeno fuzzy integral by Sugeno in the seventies. Murofushi and Sugeno proposed an integral, *Choquet integral*, which is coherent with the Lebesque integral. Choquet integral is the extension of the ordinary integral and the most natural fuzzy integral [6]. The concept of Choquet fuzzy integral is described below [10].

Let $h(x_1), h(x_2), h(x_3)\ldots\ldots h(x_n)$ be the objective evidences provided by the criteria $x_1, x_2, x_3\ldots\ldots x_n$, respectively, and g is the λ fuzzy measure, then we can construct Choquet fuzzy integral as

$$(C)\int h(.)\circ g(.) \qquad (4)$$

The above Choquet fuzzy integral reduces to the following form when X is finite:

$$E_g(h)=\sum_{i=1}^{n}\left[h(x_i)-h(x_{i-1})\right]g(A_i) \qquad (5)$$

Where,

$$h(x_1)\le h(x_2)\le\cdots\le h(x_n),$$
$$h(x_0)=0, \textit{ and}$$
$$g(A_i)=g(x_i, x_{i+1}, x_{i+2}\ldots\ldots, x_n)$$

For computing the Choquet fuzzy integral, the required inputs are the fuzzy densities (g) and objective evidences (h).

3. APPLICATION

The Bank for International Settlements studied the aspects considered by the banks in qualifying the project finance loans [11]. Figure 1 shows the aspects with their elements. The application of fuzzy integral in determining the extent to which the risk/reward profile of the project matches the risk/reward appetite of the lenders is explained using the aspects and elements of Figure 1. Prior to aggregation of information using fuzzy integral, three sets of inputs relating to the elements in the level 3 of the Figure 1 are required to be obtained. The inputs are: (i) degrees of satisfaction of the criteria; (ii) grades of importance of the criteria; and (iii) four rating levels, expressed in terms of triangular fuzzy numbers, over the possible values of the elements representing the different levels of lenders' risk/reward appetite.

3.1. Determination of the Grade of Importance

The grades of importance of the elements are elicited in terms of linguistic terms "Unimportant (UI)", "Slightly Important (SI)", "Fairly Important (FI)", "Important (I)", and "Very Important (VI)". These linguistics terms are transformed into Triangular Fuzzy Numbers to facilitate fuzzy operations. The equivalent fuzzy numbers for these linguistics terms "UI", "SI", "FI", "I", and "VI" are respectively (0.0, 0.0, 0.3), (0.0, 0.25, 0.5), (0.3, 0.5, 0.7), (0.5, 0.75, 1), and (0.7, 1, 1).

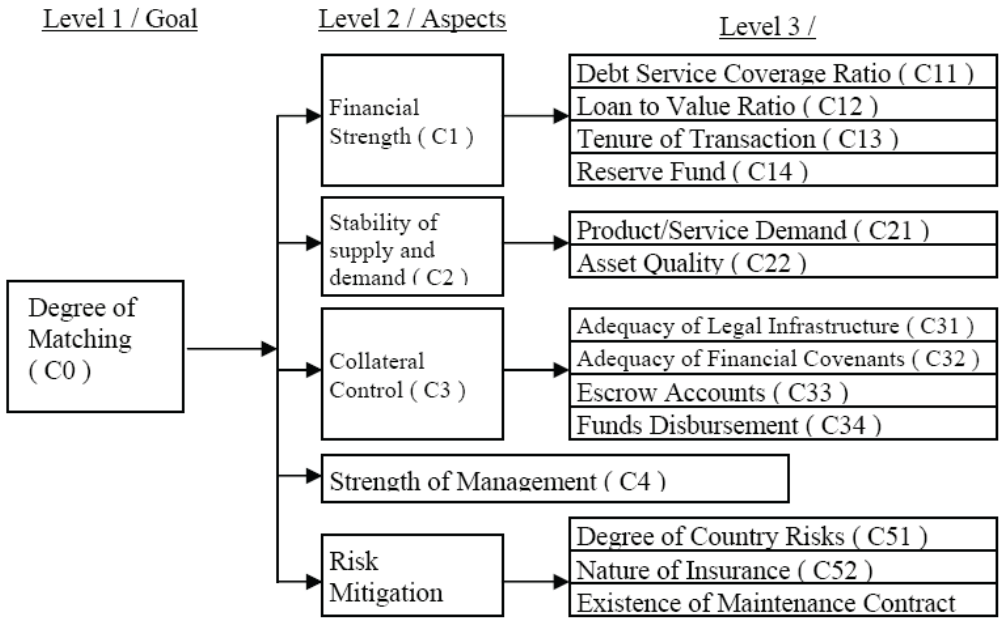


Figure 1 Aspects and Elements Used by Banks for Qualifying Project Finance Loan

The grades of importance of the project under consideration with respect to the elements are obtained in terms of the above linguistic terms. The corresponding triangular fuzzy numbers are then defuzzified using discretisation method to yield the fuzzy densities and enable computation are used to compute the value of λ. For example, the basic hierarchical structure under the parent node C1, the grades of importance of the child nodes under C1 are used to compute the value of λ for that basic hierarchical structure using Equation 3. The values of λ's for the other basic hierarchical structures under the parent nodes C2, C3, and C5 are also computed in the similar fashion.

3.2. Determination of the Objective Evidence

Prior to determination of the objective evidences, it is required to express the possible values the elements can attain in terms of four different fuzzy rating levels, namely "Very Undesirable (VU)", "Undesirable (U)", "Desirable (D)", and "Very Desirable (VD)". The elements like Debt Service Coverage Ratio (DSCR) and Loan to Value (LTV) ratio take numerical values. These values are transformed into four different triangular fuzzy numbers representing the four fuzzy rating levels. Figure 2 exemplifies the four fuzzy rating levels of numerical ratios such as DSCR. The elements, except DSCR, LTV, and Tenure of Transaction, are measured using experts' judgments. With respect to these elements, the degrees of achievement are measured in terms of triangular fuzzy numbers in the interval [0, 100]. 100 points signify the most satisfactory achievement while 0 denotes the least. Figure 3 shows the possible membership functions of one of the elements requiring subjective assessment in measuring the degree of achievement such as "Adequacy of Legal Infrastructure".

For the project under consideration, experts are asked to rate how the project performs with respect to the elements in terms of triangular fuzzy numbers (a, b, d). The values of a, b, and c refers to the least possible, most likely, and most possible values.

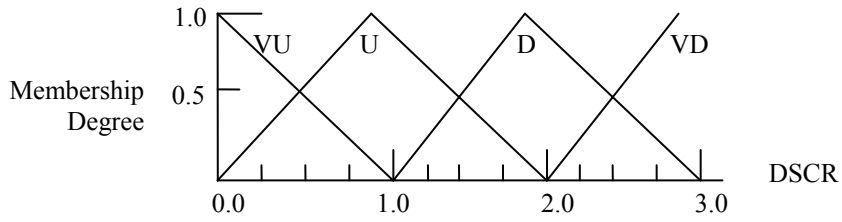


Figure 2 Membership Functions of the Four Rating Levels of DSCR

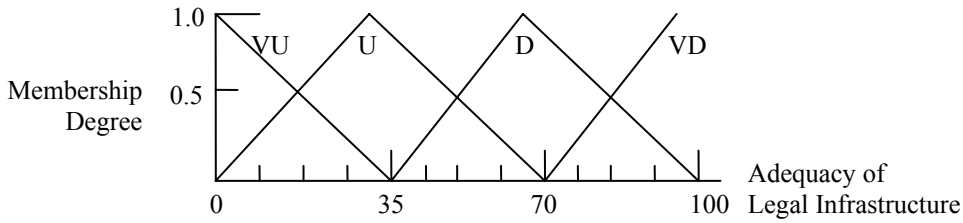


Figure 3 Membership Functions of the Four Rating Levels of "Adequacy of Legal Infrastructure"

These triangular fuzzy numbers give the degrees of satisfaction of criteria. These triangular fuzzy numbers are mapped onto the corresponding membership functions of the concerned elements.The degrees of similarity of the triangular fuzzy number, representing the degree of satisfaction of the criterion, to the four fuzzy rating levels of the corresponding element give the objective evidences of the concerned element.

3.3. Aggregation Procedure

Aggregation of the objective evidences is done in a bottom-up approach for each rating level. For the basic hierarchical structure under the parent criterion C1, the values of the objective evidences of C11, C12, C13, and C14 relative to the fuzzy rating level "Very Undesirable" are arranged in ascending order. Fuzzy measures in accordance with the different combinations of fuzzy densities of the elements as per Equation 5 are computed using Equation 3. The objective evidence of the parent node C1 with respect to the lowest fuzzy rating "VU" is computed using the objective evidences and fuzzy measures of the child nodes with the help of the Equation 5. The objective evidences with respect to the lowest rating level are computed in similar fashion for the parent nodes C2, C3, and C5. Using the objective evidences of C1, C2, C3, C4, and C5 and the corresponding fuzzy measures objective evidence with respect to the lowest rating level is computed for the node at the level 1. The same aggregation procedure is adopted for the entire hierarchical structure for the remaining fuzzy rating levels. The objective evidences of the node at level 1 derived from the aggregation process give the measure on the degrees of matching with respect to the four rating levels. Matching to a significant extent to the rating levels "D" or "VD" signifies a match between the risk/reward profile of the project and risk/reward appetite of the lenders.

4. CONCLUSIONS

Lenders before making credit decision aggregate information on the aspects of the PPP projects to determine whether the risk/reward profile of the project matches their risk/reward appetite. The nature of the information available at the time of decision making is not precise and accurate. The review of literature on information fusion has indicated Choquet fuzzy integral as one of the aggregation operators for fusion of imprecise and inaccurate information. This paper discusses the

concepts of Choquet fuzzy integral and fuzzy measure. The paper also elaborates the application of Choquet fuzzy integral to assess the degree of match between the risk/reward profile of the project and risk/reward appetite of the lenders with the help of the aspects used by the banks in qualifying project finance loans. The aggregated information on the degree of match can facilitate lenders to make decision on advancing project finance loan to PPP projects.

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MODEL OF PROACTIVE PROBLEM-SOLVING FOR CONSTRUCTION KNOWLEDGE MANAGEMENT

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ABSTRACT

Construction is an experience-based discipline, knowledge or experience accumulated from previous projects plays very important role in successful performance of new works. More and more construction organizations have adopted commercial Knowledge Management Systems (KMSs) for developing their own Knowledge Management (KM) functionalities. The existing KMS's are mostly developed based on Communities of Practice (COPs) for knowledge sharing and exchange. Such approach founds on the reactive problem-solving (RPS) method. That is, the problem raised by the questioner in the COP has to passively "wait" for the members to respond (or react). Previous research indicates that such RPS approach may suffer in poor time and cost effectiveness. This paper proposes a proactive problem-solving (PPS) approach called Model of Proactive Problem-Solving (MPPS) for KMS. Unlike RPS, the PPS proactively solves the problem based on lessons-learned from previous projects. Should the solution is not available; the MPPS dispatches the problem to the most appropriate domain experts so that the problem can be tackled timely and efficiently. The MPPS is described in details, and an example construction KMS that adopts the proposed MPPS is demonstrated. It is found that the proposed MPPS has significant potentials to improve the performance of KMS for construction organizations.

KEYWORDS

Knowledge Management, Problem-Solving, Knowledge Map, Lessons-Learned, Proactive

1. INTRODUCTION

Problem solving is the center of the daily operations for construction organizations [1]. Since Construction Engineering is an experience-based discipline, knowledge accumulated from previous projects is the key to solve similar problems in the future projects [2]. Current practice of knowledge management system (KMS) has established operational framework and platform for construction knowledge management. However, most existing KMSs were based on so-called "reactive mode" of KM. That is, the problem raised by the questioner has to wait (passively) responses from members of the Community of Practice (COP) of the KMS. Previous research has indicated that such approach can be a bottleneck to the performance of the KMS due to poor time and cost

effectiveness of the reactive problem-solving (RPS) model [2].

It is very desirable to improve the drawbacks of the traditional RPS for the KMS of construction organizations, such as the contractors and A/E firms, where timeliness of problem-solving is crucial to the survival of the firm. In other words, a proactive problem-solving (PPS) approach is expected not to passively "wait" responses from the members of COP; but rather proactively "tackle" the posed problem with the most appropriate solution from lessons-learned before. While the solution is not available from historic lessons, it is expected to "proactively" seek the domain expert who holds the most related implicit knowledge for the problem to solve the problem manually.

In order to establish such approach, several functionalities of a KMS should be developed including: (1) a knowledge classifications scheme (or a Knowledge Map) that appropriately represents the knowledge asset of the organization and accurately describes problem encountered; (2) a representation scheme for description of the expertise of the domain experts (or an Expert Map), which properly reflects knowledge (expertise) that the domain expert accumulated previously; (3) a set of text mining algorithms for searching of the most relevant lessons learned in previous project; (4) a problem dispatching scheme for associating the posed problem with the most appropriate domain expert; and (5) a repository of lessons learned from previous projects and the required functions of lesson learning.

In this paper, a conceptual model of proactive problem-solving, namely Model of Proactive Problem-Solving (MPPS), is proposed to provide the above-mentioned functionalities and overcome the disadvantages of traditional RPS. The proposed MPPS provides a systematic framework for building a more intelligent knowledge management system (KMS) in four aspects: (1) it acquires knowledge systematically and continuously from daily knowledge management activities of a KMS; (2) it constructs a more efficient structure for the knowledge (domain expertise) and human resource (domain experts) management of a KMS; (3) it solves problems proactively unlike the traditional passive/reactive RPS approaches; (4) it combines the merits of traditional KMS and automatic answering system (AAS) that make the best use of the knowledge of the organization.

The reset of the paper is presented in the following manner: in the second section, related previous researches are reviewed to provide backgrounds for the proposed MPPS; then, the theoretical framework for MPPS is proposed; in the fourth section, a preliminary implementation of the proposed MPPS in the KMS of a local leading consulting firm is presented to demonstrate the applicability of the proposed MPPS; finally, assessments of the preliminary MPPS implementation are summarized and conclusions are drawn based on research findings.

2. REVIEW OF RELATED WORKS

The term "Proactive Problem-Solving" is not found in the literature. However, building blocks of MPPS described pin the problem statement can be related to some existing works that found the base of MPPS.

2.1 Problem-Solving in Construction

Li and Love [1] developed a framework of problem-solving for construction engineering and management. Their research found that construction problems pose several characteristics that should be tackled in order to solve them quickly, correctly, and cost-effectively, such as ill-structure nature, inadequate vocabulary, little generalization and conceptualization, temporary multi-organization, uniqueness of problems, and hardness in reaching the optimal solution. Two areas of problem solving researches tackle the above-mentioned issues: the cognitive science and decision support system. In addition to these two areas, Yu et al. [2] propose a new approach called Knowledge Management integrated Problem-Solver (KMiPS) to solve emergent construction problems. Their works proved that the KMiPS achieved both quantitative and qualitative benefits better than traditional problem-solving approaches.

2.2 Knowledge Classification and Knowledge Map

Kim et al. [3] proposed a practical method for capturing and representing knowledge that is

critical in knowledge management. The method employs a knowledge map as a tool to represent knowledge of a firm. The procedure consists of six steps: (1) defining organizational knowledge; (2) analyzing process map; (3) extracting knowledge; (4) profiling knowledge; (5) linking knowledge; and (6) validating map knowledge. Effective knowledge maps help identify intellectual capital, socialize new members, enhance organizational learning, and anticipate impending threats and/or opportunities [4]. Caldas et al. [5] proposed an automatic document classification method based on text mining algorithms. Their work successfully classified 4,000 documents automatically with the Construction Document Classification System (CDCS) they developed.

2.3 Automatic Answering System (AAS)

Automatic Answering System (AAS) serve as a domain expert who can answer the question posed by questioner instantly. Various types of AAS's have been developed in construction industry. The Advanced Construction Technology System (ACTS) was developed in University of Michigan at Ann Arbor by Ioannou et al. [6]. ACTS provides a technology information system for construction planners and managers to select the most appropriate state-of-the-art construction technologies during the project planning stage. More than 400 technologies are recorded with 25 attributes such as general description, cost benefit, construction constraints, special application, operation environment, test criteria, etc. The Architecture and Engineering Performance Information Center (AEPIC) was developed by Loss at the University of Maryland [7]. The AEPIC provides information of failures so that the mistakes won't be made again. The On-Line Reference Library (OLRL) was developed by Bechtel Inc. to provide the engineers with real-time reference manuals of SPECs. The Civil Engineering Information System (CEIS) of Kajima Corp. is similar to ACTS and OLRL, which stores more than 300,000 documents [8]. Even though the abovementioned construction information systems provide some features of AAS, most of them are database system equipped with search functions. None of them completely fit the requirements of an AAS, such as automatic problem characterizing, intelligent information retrieval, problem dispatching, and solution repository. Moreover, they are information system rather than problem-solving system.

2.4 Lessons-Learned System

There have been many existing lessons-learned systems reported in literature, which provides references for developing MPPS. The Hypermedia Constructability System (HCS), Indiana Department of Transportation (INDOT) was developed in collaboration between INDOT and Purdue University [9]. The HCS stores historic lessons-learned in multi-media format so that construction engineers can learn from previous lesson more effectively. The Constructability Lessons Learned Database (CLLD) & Integrated Knowledge-Intensive System (IKIS) were developed by Kartam and Flood [8][10] to provide a repository for previously learned lessons. The major difference between CLLD & IKIS and the abovementioned lessons-learned systems is that the latter verifies historic lesson-learned by the domain experts before storing in the database. The Construction Industry Institute (CII) developed a Lessons-Learned Wizard (LLW) with the package of constructability program [11]. The LLW is a computer aided information system that helps the engineers to record and retrieve the lessons learned from historic projects.

3. PROPOSED MODEL OF PROACTIVE PROBLEM -SOLVING (MPPS)

The proposed MPPS consists of four major components: (1) Knowledge/Expert Map (K/EM)—providing classification scheme for knowledge and expertise of the domain experts; (2) Automatic Problem Answering (APA) module—solving the posed problem automatically based on the historic problem-solving cases and lessons-learned; (3) Automatic Problem Dispatching (APD) module—dispatching the posed problem to the most appropriate domain expert when the problem cannot be solved by APA; (4) Lesson-Learned Wizard (LLW) - accumulating historic lessons-learned based on the classification scheme of K/EM.

3.1 Knowledge/Expert Map (K/EM)

The proposed MPPS is kernelled at the knowledge and the expert holding the knowledge. In MPPS, the domain knowledge is modeled by Knowledge Map; while the domain experts are represented by Expert Map. The Knowledge Map and Expert Map (K/EM) provide the ontology for modeling the knowledge repository of the construction firm. A Multi-dimensional Knowledge Ontology (MKO) scheme is adopted for the following reasons: (1) effective and efficient classification of knowledge documents (e.g., proposals, plans, work journals, final reports, etc.) and problem-solving lessons-learned; (2) correct and accurate description of problem; (3) provides a basis of Expert Map. The MKO scheme represents a knowledge document (KD) or a lesson-learned (LL) with a vector of codes including: (1) lifecycle code—describing the time reference of the knowledge, such as all life cycle, feasibility analysis, comprehensive planning, basic design, detail design, construction/installation, testing, operation/maintenance, recycle, change, etc.; (2) service/product code—describing the service/product related to the knowledge, such as bidding proposal, execution plan, QA plan, procurement plan, SPEC, alternative report, inspection report, calculation report, drawing, etc.; (3) profession code—the profession classification of the knowledge, such as administration, HR, civil (excavation, refill, site preparation, piping, etc.), structural (RC, PC, SS, underground construction, retaining structure, etc.), architecture (urban planning, building design, interior design, landscape, model, finishing, etc.), geotech (site investigation, pile, foundation, drainage, rock, stability, etc.), survey, highway, transportation, logistics, airport, hydraulics, harbor, material testing, etc; (4) sub-class keywords—for more specific description of the knowledge. An example vector (13, 20, 35, 5) can be interpreted as "the basic design criterion for segmental precast bridge construction".

The Knowledge Capacity Matrix (KCM) is proposed for representing the expertise of the domain experts. The KCM describes a domain expert with a row vector containing three dimensions: (1) seniority—recording the professional seniority (in years) of the expert; (2) intensity—recording the intensity of work (work hours/ seniority years) of a specific domain (described by MKO), which reflects the strength of expertise of the expert in a specific domain; (3) enthusiasm—recording the historic performance of the expert in participation of KM activities automatically provided by the KMS of the firm.

3.2 Automatic Problem Answering (APA) Module

The Automatic Problem Answering module (APA) is an automatic problem-solving system (APS) that searches the solution database to provide the most appropriate answer to the problem. Several requirements are expected for an ideal APS [12]: (1) it must tolerate simple errors; (2) it must embody a degree of "common sense"; (3) it must have a relatively large and complete vocabulary for the subject matter to be treated; (4) it must accept a wide range of grammatical constructions; (5) it must be able to deal sensibly with partly understood input; and (6) it must be capable of providing the information and computations requested by the user. Previous research has developed APS for internet service [13] and tutoring assistant [14]. The APA module is planned as shown in Figure 1 based on the APS of Wu et al.[14] .

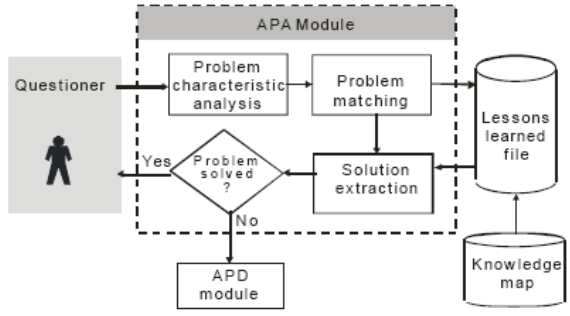


Figure 1 Conceptual Design of APA Module

In Figure 1, problem is posed by the questioner. The characteristics of problem are analyzed by APA. Then, APA searches the historic lesson-learned file (LLF) to find the most relevant lessons of the historic lessons. Finally, the solution is extracted from the relevant lessons based on a similarity measurement algorithm proposed by Wu et al. [14] as described below:

$$S_i = (\mathrm{N} - R_i) \times 0.2 + S(\mathrm{F}_i) \times 0.5 + S(A_i) \times 0.2 + S(T_i) \times 0.1 \quad \cdots\cdots \quad (1)$$

where, $$S(X) = \frac{|KQ \cap KX|}{|KQ|} \cdot 0.8 + \frac{\sum_{j=1}^{n} L_j}{\mathrm{LX}} \cdot 0.2 \quad \cdots \quad (2)$$

S(X): similarity measurement of the semantic fragment *X* to the problem;
N: number of supplement materials considered;
R_i: page rank of the supplement materials that contain fragment *i*;
F_i: content of the semantic fragment *i*;
A_i: abstract of the supplement materials that contain fragment *i*;
T_i: title of the supplement materials that contain fragment *i*;
$KQ = \{K_1, K_2, \ldots, K_n\}$: keyword set of the problem;
$KX = \{K_1, K_2, \ldots, K_m\}$: keyword set of the fragment *X*;
LX: sum of word length of the fragment *X*;
L_j: total word length of occurrences of K_j in *X*.

If the solution is found (according to a predetermined similarity threshold), it is replied to the questioner. However, if the solution is not found, the problem is unsolved and diverted to APD module.

3.3 Automatic Problem Dispatching (APD) Module

Figure 2 shows the conceptual planning of the APD module. In figure 2, the unsolved problem is posed to KMS as an emergent problem and diverted to APD module at the same time. In APD module, the problem characteristics analyzed in APA module is used to find the most appropriate domain experts based on the Expert Map described previously. Then, the problem is dispatched to the most related domain experts for possible solution. Finally, the experts respond to the problem in a special COP called SOS of the KMS.

3.4 Lessons-Learned Wizard (LLW)

The LLF required in APA module is constructed by a Lessons-Learned Wizard (LLW) proposed by the Construction Industry Institute (CII) [11].The LLW captures lessons-learned right after a problem is solved in the KMS. The LLW is integrated with an internet questionnaire surveying system that allows the questioner to evaluate the solution he/she obtains.

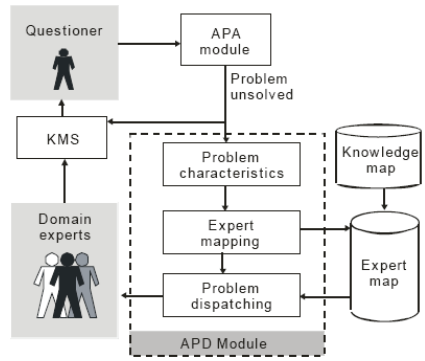


Figure 2 Conceptual Planning of APD Module

The LLF associated with the problem contains the following information: (1) the topic of the problem—titling the problem; (2) the description of the problem—detailed description of the problem; (3) the questioner—the name of questioner; (4) the solution—detailed description of the solution; (5) the responder—the name of the responder who provided the most related solution; (6) appendices—the supplementary materials for the solution;(7) benefits assessments - assessments of all benefits resulted by the solution including time, cost, quality, technical improvement, regulation impacts, etc. The LLFs are classified by the MKO scheme of Knowledge Map.

3.5 Integrated Model of Proactive Problem Solving (MPPS)

The integrated framework of MPPS is depicted in Figure 3. In the integrated framework, MPPS solves construction problems in two modes: (1) Automatic problem answering mode (APA mode)—the problem solving process is shown in Figure 3 as bold solid arrows, where the solution is searched automatically from historic lessons-learned based on problem characteristics; (2) Automatic problem dispatching (APD) mode—the problem solving process is shown in Figure 3 as dashed arrows, where the unsolved problems (by APA mode) is automatically

dispatched to the most related domain experts according to the problem characteristics and the Knowledge Capacity Matrix (KCM). The functions of problem-solving in the traditional KMS is preserved and exercised in MPPS as shown in Figure 3 where the unsolved problem is posted in the COP of the KMS before entering the APD mode.

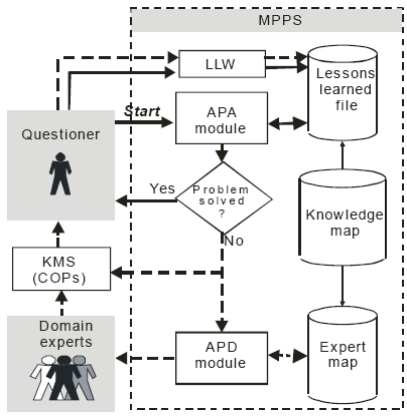


Figure 3 Integrated Framework of MPP*S*

Both the problems solved in APA and APD modes are new lessons learned for future problems. This process is actually a verification of the knowledge to generate a higher level of intellectual asset called "wisdom". This process is performed by LLW as shown in Figure 3.

4. PRELIMINARY IMPLEMENTATION

The proposed MPPS has been implemented in the KMS of a leading A/E consulting firm in Taiwan, CECI. The KMS of CECI is developed based a commercial platform—Microsoft SharePoint®. However, the original software has been customized to fit in the specific requirements of the firm. One of the major customizations is the specialized emergent problem-solving system, called SOS, to provide real-time aids for engineers/managers who are encountered with emergent problems. The SOS system has been proved to be very beneficial to the firm. Both tangible and intangible benefits were resulted significantly [15].

4.1 Problems Faced in the Existing System

The SOS system is actually a specialized COP that includes all staffs of the firm as its members. Once a problem is posed by a questioner in SOS, it will prompts automatically on the entry page of the KMS of every member. The essential problem of existing COP in solving emergent problems is that the problem posed in the COP should "wait" the domain experts to provide solutions. Such "passive" mode of problem solving assumes that the domain experts can "see" the problem and respond with their solution timely. However, previous research found that such RPS approach has caused inefficiency of timeliness and cost-effectiveness of the KMS [2]. A proactive problem-solving (PPS) approach should be developed.

4.2 Preliminary Implementation

The proposed MPPS has been preliminarily implemented in the SOS of CECI at current stage. A prototype Proactive Problem Solver (PPS) is developed and tested. The prototype PPS consists of all four required elements of MPPS: (1) K/EM—a preliminary knowledge/expert map is constructed based on the MKO scheme; (2) APA module—a preliminary APA module is programmed to perform APA problem-solving mode; (3) APD module—at the moment of writing this paper, the preliminary APD module is still under construction; (4) LLW—a preliminary lessons-learned file is established based on the 439 historic problem-solving cases of SOS system accumulated in the last three years. Figure 4 shows an example of Expert map. Figure 5 and 6 show interface of preliminary APA module.

5. ASSESSMENTS OF PRELIMINARY IMPLEMENTATION

As the proposed MPPS is still under development, it is preliminarily implemented in the SOS system of the KMS of CECI. Assessments are concluded from the preliminary implementation as follows. The effectiveness of MPPS is assessed according to two criteria: timeliness and cost effectiveness. The time required to solve a case problem by the original SOS is averagely 2.7 days. In MPPS, the required time to solve the same problem is within seconds if the relevant lessons are available for the problem in LLF, which is negligible compared with the original SOS. This is very desirable for emergent problem solving. The cost effectiveness of MPPS is as impressive as timeliness; since most

costs spent in problem solving are man-hours of the staffs participating in problem solving. According to 439 case study data, the average problem-solving man-hour cost is reduced from TWD 4,075 (USD 123.5) per problem to nearly zero in MPPS.

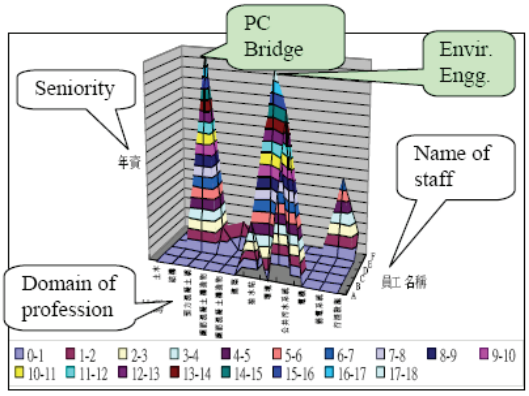


Figure 4 Example of Preliminary Expert Map

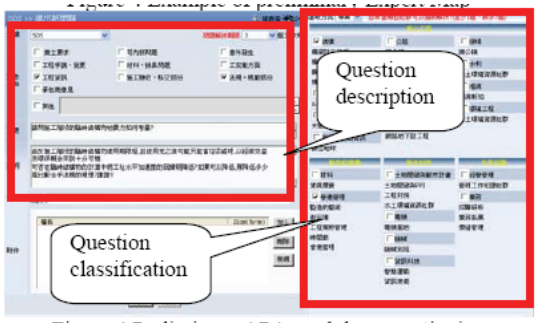


Figure 5 Preliminary APA Module-Questioning

The correctness of MPPS is assessed by verifying the solutions generated by APA module with those provided by the domain experts. This is currently conducted by the research team. The preliminary result is not satisfactory due to the high rate of incorrect solution. The research team is solving the problem by providing APA with specialized corpus for domain problems.

The extendibility of MPPS is another important issue concerning the future implementation of MPPS to other elements of the KMS as the preliminary implementation was focused on problem-solving. Since the KMS is cored with problem solving, the proactive problem-solving mechanism developed in MPPS provides a problem-solving engine that can enhance the efficiency of all KM activities including problem socialization, knowledge generation and sharing, solution finding, and other KM issues. The extendibility of MPPS is also confirmed.

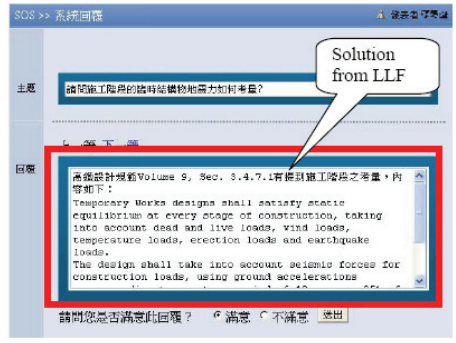


Figure 6 Preliminary APA Module—Answering

6. CONCLUSIONS AND FUTURE WORKS

This paper presents the preliminary result on the development of the model of proactive problem-solving (MPPS). All elements of MPPS are described in details. The preliminary implementation of the proposed MPPS in the KMS of a local leading A/E consulting firm, CECI, is demonstrated. Assessments of the preliminary implementation are discussed to show the applicability and potentials of the proposed MPPS. The proposed MPPS provides a new paradigm for problem-solving, which completely reforms the traditional passive/reactive mode of problem-solving approaches. It is concluded that the proposed MPPS is very powerful in improving the timeliness and cost effectiveness of the traditional KMS. It is beneficial to construction firms who are facing emergent problems in daily operations.

Even though preliminary results show promising benefits of the proposed MPPS, future verifications are required to validate the implementation of MPPS including: (1) quantitative evaluation of time and cost effectiveness; (2) verification of correctness of solutions inferred by MPPS for all

types of domain problems; (3) integrated computer system for MPPS need to be developed and verified to ensure the implementation of the proposed MPPS.

7. ACKNOWLEDGMENT

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A DECISION THEORETIC FRAMEWORK FOR INFORMATION SYSTEM PLANNING IN THE CONSTRUCTION INDUSTRY

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ABSTRACT

Automation and Information Systems (IS) implementation in the construction industry have evolved in scope and scale of effects over the years. With their growing importance, there is a need for a more practical IS planning approach. Along with the alignment of Information Technology Strategy with the overall corporate strategy of the firm, the Critical Success Factor method, the Value Chain method and other Opportunity frameworks emphasize the prioritization of the key processes for Information Systems planning. The effects of information technology on organizational hierarchy, internal power structures and control flows have been well documented. In the specifics pertaining to the construction industry, this involves a considerably risky transition from a multilevel hierarchy organizational structure to a relatively decentralized, flat organization. This paper presents a decision theoretic framework for Information Systems planning in the construction industry. The objective is to provide a comprehensive and unified approach for analysis and evaluation of the roles, scale and scope of Information Technology in the construction firm. This presupposes elicitation of requirements from a diverse set of stakeholders – managers, workers, suppliers and so on. One common problem is the difficulty in maintaining a sufficient degree of formalization and uniformity of structure to ensure effective communication across distributed design teams, while also ensuring adaptability and flexibility in the approach to accurately capture requirements elicitations of different users. The Cognitive Dimensions framework is an approach to analyzing the usability of information artifacts: Here, we apply it to the requirements elicitation process for IS planning in the Construction Industry.

KEYWORDS

IS Planning, Cognitive Dimensions, Requirements Engineering, Human-Centered Systems

1. INTRODUCTION

Information system (IS) success is dependent upon the effectiveness of requirements elicitation. A significant portion of IS development failures are attributed to incomplete and inaccurate information requirements [12, 13, 14, 15, 16, 17, 18, 19]. Some studies [5], suggest that as many 90% of large software projects that fail, owe their failure to the difficulties encountered in accurately capturing system requirements. Incomplete or inaccurate requirements also result in major post-implementation revisions [18] that account for a significant portion of the maintenance costs of IS [20, 21, 22]. The cost of correcting post-implementation problems is considerably higher than that of making changes earlier in the development process [24, 23, 22]. Thus, research that identifies methods for improving the completeness and accuracy of requirements obtained during the requirements elicitation process can provide significant benefits to IS planning efforts. Software support tools have been developed to support all processes of software development, including requirements engineering. However, one area of requirements engineering where support is currently very limited is the area of elicitation.

This is a difficult area to support because of the wide range of stakeholders who may be involved in the process, the different notations and vocabularies used by these stakeholders and the incompleteness of the requirements at this stage. There is therefore some scope for managing unstructured information during the elicitation process [3]. From past work in this field, there is evidence that more than "hard" studies that yield improvements in implementation phases, the outcomes of the requirements engineering processes can be improved significantly by improving the cognitive strategies of systems analysts [14, 25, 26, 27, 28]. Research in this area has examined cognitive processes that impacts analysts' ability to obtain complete and accurate requirements [29]. There is also some work on Cognitive Mapping Techniques and Causal, Semantic and Concept mapping have been explored [31], as well as Activity Theory [32]. The gap we see in the existing literature is for a formal methodology to evaluate the cognitive processes of the user and the requirements team on a common platform. Such an approach is especially promising for the construction industry, where the range of user profiles is very diverse, and the processes users follow are the root cause of information intensity in the system, rather than the end product.

The framework we propose in this paper is aimed at overcoming the cognitive limitations that lead to improper elicitation process design. Our Cognitive Dimensions Framework is aimed at ensuring that the primary task of requirements elicitation – that of translating user needs to requirements, is met.

2. CHALLENGES IN REQUIREMENTS ELICITATION

As per [30], Requirements Elicitation implies learning, uncovering, extracting, surfacing, or discovering needs of customers, users, and other potential stakeholders in the System to be developed. Requirements engineering processes are dominated by human, social and organizational factors because they involve a range of stakeholders from different backgrounds and with different individual and organizational goals [2]. Common requirements problems which arise [2] are

- The requirements don't reflect the real needs of the customers of the system
- The requirements are inconsistent and/or incomplete
- It is expensive to make changes to requirements after they have been agreed
- There are misunderstandings between customers, those developing the system requirements and software engineers developing or maintaining the system

Requirements elicitation is constrained by not only the user-side problems stated above but also the cognitive limitations of analysts, as per [1].

3. USABILITY OF THE ELICITATION PROCESS

The concept of usability as applied to software with graphical user interfaces (GUIs) - developer tools, word processors, or e-mail clients, is well understood. We expect these tools to let us perform a given set of tasks and to work the way we expect them to. If any of the products that we use fail to work in the way that we expect them to, we generally label this as poor design or usability [7]. There can be many causes for poor product usability or design; for example, users may not be aware of the actions that they can take with a product. Likewise, they may not be able to predict the result of performing some action and hence might be reluctant or less inclined to perform that action for fear of the potentially negative consequences that might ensue. Or they misinterpret the actions that they can take and the results of those actions. It is worthwhile to develop the concept of usability as applicable to the product of the requirements elicitation process of information systems projects in the construction industry, as the objective here too is to minimize misinterpretations both from the users and the requirements team, ensure active participation and maximize predictability of actions for the users.

4. RATIONALE FOR CHOICE OF CD FRAMEWORK

Cognitive engineering offers a principled approach to the design and development of human-centered systems. The cognitive engineering process integrates an analysis of the cognitive and collaborative demands of a user engaged in work with an iterative design, implementation, and evaluation approach to developing support tools [4]. The cognitive dimensions framework has evolved from research done at Cambridge University, UK on programming language usability. In this paper, we draw the analogy between the programmer in the case of an API and the end user in the case of software being developed. We contend that the layers of abstraction that the API presents to the programmer to access the functionality of the programming language are of a similar nature to the layers of abstraction that software presents to the end user to access the functionality of the underlying processes, and therefore, the theories of usability that are applicable in the context of API can be fruitfully extended to requirements elicitation. The cognitive dimensions we have chosen here have been developed for the representation of notations such as music and Morse [9] and have also been successfully applied for API usability studies [7].

5. COGNITIVE DIMENSIONS

The cognitive dimensions framework presents a set of 12 different dimensions (or factors) that individually and collectively have an impact on the way that users interact with the requirements elicitation process and on the way that users expect the requirements to be translated into a working system. These dimensions are as follows:

1. Abstraction Level

They specify the minimum and maximum levels of abstraction exposed to the user, and are a measure of the type and number of abstractions that the user has to contend with. These types are primitives, factored or aggregate.

2. Learning style

The learning requirements posed by system, and the learning styles comfortable for a targeted user, in the context of the given system.

3. Working framework

The size of the conceptual chunk (user working set) needed to work effectively. It specifies the context that users need to maintain when working with a process.

4. Work-step unit

It specifies the magnitude of the task that must/can be completed in a single step.

5. Progressive evaluation

It describes the extent to which partially completed description can be utilized to obtain feedback on system design.

6. Premature commitment

This factor measures the amount of decisions that users have to make when using the system, and the consequences of those decisions.

7. Penetrability

Penetrability defines the extent to which the requirements process facilitates exploration, analysis, and understanding of the overall system components, and how targeted users go about relating and retrieving what is needed.

8. Elaboration

Elaboration is a measure of the extent to which the system components must be adapted to meet the needs of targeted users.

9. Viscosity

This is a measure of the barriers to change inherent in the system process and how much effort a targeted user needs to expend to make a change.

10. Consistency

This indicates the extent to which the rest of the tasks in the system can be inferred once part of it is finalized.

11. Role expressiveness

This measures the apparentness of the relationship between each component exposed by the requirements process and the system as a whole.

12. Domain correspondence

This is a measure of how clearly the system components map to the domain and any special tricks that the user needs to be aware of to request some functionality. User's domain models will not necessarily be the same as requirement team's.

6. RELEVANCE TO THE CONSTRUCTION INDUSTRY

A principal characteristic of construction industry projects is the distributed nature of the project team. The industry is generally regarded as relatively inefficient when compared to other sectors such as manufacturing and electronics [35]. Inefficiencies arise in the construction industry because the fragmented groups have difficulty coordinating their efforts and combining their individual contributions [33]. The industry is characterized as being fragmental in participants and processes. Participants of the industry range from large international enterprises to small local businesses all with various capabilities and interests. Multiple parties are involved in the industry business activities, such as owners, designers, contractors, suppliers, manufacturers, and supporting service providers. The process is considered as fragmented due to the participation of different parties at different stages in the construction process (design, procure, construct, and operate), as well as many specialized systems of components (structural, electrical, mechanical, etc.) that make up the final product. Due to the number of participants involved, the complexity of the product, and the short term of execution, the volume of information flowing through the construction processes is extensive and complex [34]. Given these factors, it is unlikely that one common system design would map to the mental models of tasks of all the stakeholders. With the Cognitive Dimensions Framework applied iteratively to each unit of the system design independently of the requirements elicitation process, this mismatch can be reduced.

7. PROCESS FLOW

The following section explains the process to measure and apply these 12 cognitive dimensions in the context of the requirements process. We use as an example the cognitive dimensions framework applied to a Systems Requirements study for IS planning at *Dwaraka Constructions,* a medium sized Road construction firm with operations in Kadapa District, Andhra Pradesh, India. The firm is responsible for laying and maintaining various road projects across Kadapa district. The operations of the organization revolve around Material, Machine and employees/labourers. While the specifics of the firm or the system need not concern us, the methodology of application of the CD framework is illustrated here.

The process flow is thus: First, the study is initiated after a request for proposal. The business processes of the firm are analyzed, and the stakeholders in the new system identified as being Top Management, Resource Managers, Machines-In-charge, Plant Managers and Financial Managers. The Requirements Elicitation process consists of identifying, formalizing and documenting the requirements of these diverse user groups. The end-product is a set of Requirements Specifications Documents (Process Flow, Functional Specifications and Database Structure Documents). Now, we apply the CD framework to the proposed system and to the personas of the stakeholders, independently.

7.1. CD Scores for the Proposed System

The System (as specified in the Requirements Specifications Document) is subdivided into modules, on the basis of user group. Here, the modules would be areas of the system to be used by the top management, those used by the resource managers, and so on. Each module is evaluated along the 12 dimensions on a scale of 1-4. The scores of each module for the CD parameters are noted. This is a subjective assessment, performed by the system designers.

7.2. CD Scores for the User Groups

The user groups identified at the requirements elicitation phase are now separately studied to evaluate their scores along the 12 cognitive dimensions. Again, this is a subjective assessment, performed with inputs from the top management. Within each user group, each user

will have a unique set of CD scores. For the present example, we have taken a 'representative user' of each user group

7.3. CD Radar

The CD Radar for each module consists of 2 graphs: The plot of the CD scores for the System and those for the User Groups. It is a convenient visualization tool to understand the gaps between the actual user requirements and the proposed system design. Figure 1 shows the CD Radar for PM_Module – The project management module which will be used by the resource managers.

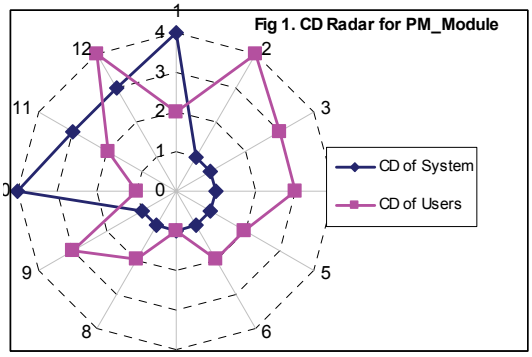


Figure 1 CD Radar for PM_Module

Table 1 CD Scores for PM_Module

CD no.	System	Users
1	4	2
2	1	4
3	1	3
4	1	3
5	1	2
6	1	2
7	1	1
8	1	2
9	1	3
10	4	1
11	3	2
12	3	4

The closeness of fit between the two curves is a measure of the degree of match between the user's actual requirements and the proposed system design. For instance, in Table 1, for Cognitive Dimension 4 – Work Step Unit, the System scored 1 and the User Group (Resource Managers) scored 3. This implies that the magnitude of task that the PM_Module would typically perform at one step is much lower than the level at which the users are most comfortable at. A corrective measure would be to revise this aspect of the system design. If the gap for any CD parameter deemed critical is beyond the tolerance levels, then the system design may be modified by modifying the elicitation process itself and performing the requirements phase again. This is an iterative process.

7.4. Using Personas

It may not be easy to figure out the right adjustment for gaps, to the requirements process, since user groups are not homogeneous. We use personas to represent our understanding of who our users are, and then plot the CD Radar for the 'representative persona' of each user group. Using the API Usability Study's [7] definitions of three main user profiles we describe the stereotypical behavior of three main user group types: Opportunistic, Pragmatic and Systematic. The rationale for fitting these user types from software development to the construction industry is that this is a fairly generic classification, and is based on the cognitive processes users follow to do a task, rather than the task itself. Table 2 gives the preferences of cognitive dimensions by the different persona types. Representative Personas for each user group, once found– systematic, pragmatic and opportunistic – will in turn drive the system design and next iteration of requirements elicitation.

8. CONCLUSION

To ensure that we know how users expect requirements to translate to a working system, designing the requirements elicitation process through human-centered design is a starting point. We can use the cognitive dimensions framework to describe how well the process meets our users' requirements and to gather feedback from users. The CD framework enables a closer match between information requirements gathered by the requirements team and the actual user needs and provides a platform with which to

Table 2 CD Preferences by User Type

	User Type Preference		
Dimensions	**Systematic**	**Pragmatic**	**Opportunistic**
Abstraction Level	Prefer Primitives Tolerate Aggregates	Prefer Aggregates Can't tolerate Factored	Prefer Aggregates
Learning Style	Top-Down	Stepwise	Minimal Incremental
Working Framework	System, Reengineered	Global	Local
Work-Step Unit	Abstraction Dependent	Functional Incremental	Local Incremental
Progressive Evaluation	High Frequency Abstraction Dependent	Low to Medium Frequency Tolerated	Undesirable
Premature Commitment	Prefer Low	Prefer Low	Prefer Low
Penetrability	Expansive Extensive	Context Driven	Snapshot
Elaboration	High Control	Fine Tune	Ready use
Viscosity	Low High if High Control	Low	Low
Consistency	High	High	High
Role Expressiveness	Prefer Transparent Tolerate Opaque	Prefer Transparent Tolerate Plausible	Transparent
Domain Correspondence	Prefer Direct Tolerate Arbitrary	Prefer Direct Tolerate Plausible	Direct

understand the results of the analysis. It helps understand causes, not symptoms and enables the user-centered approach for requirements engineering. Effective requirements elicitation depends upon the ability of users and analysts to understand and appreciate one another's worlds: The CD framework provides a common language to foster this understanding.

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A METHODOLOGY FOR CONSTRUCTION RESEARCH PROGRAM DEVELOPMENT

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ABSTRACT

Technology fusion is a new way of improving efficiency and effectiveness of construction technology research and development. Technology fusion indicates an interdisciplinary approach of combining different technology areas. To succeed in developing technology fusion-based construction research plans, two major approaches are adopted in this study: technology push investigation and market needs identification. Technology push investigation is to understand what types of technology are pushing the industry for improved business practices. Market needs are identified based on expert panel discussion, questionnaire-based survey, and committee reviews, in order to extract a range of technologies that are needed in the present construction industry. Through this process, 124 technology fusion-based research program candidates, which were first discovered from technology push and market demands investigation, were refined and reduced into 36 research programs. This paper presents the systematic methodology for developing the technology fusion-based research programs.

KEYWORDS

Construction Research, Technology Fusion, Technology Program Planning

1. INTRODUCTION

Technology fusion is one way of developing advanced construction technology. The technology fusion is defined as "a systematic interdisciplinary effort to destroy the walls between many science and engineering disciplines [1]." Combining state-of-the-art information technology, bio technology, nano technology, and environmental technology acts as a catalyst for enhancing construction research and development program. Through the interdisciplinary research and development, construction technology can be innovated.

Sometimes, research programs for technology development are not based on the needs of market. New technologies that were developed with significant investments often times end up not being used at all in the real business practices. Therefore, attentions need to be paid to the current and future needs of the market and society. On the other hand, throughout the history of mankind, technologies have been the major factor that changes the society. New paradigms of business practices have always been the result of new technology developments. In summary, technology push and market demands both should be carefully considered to identify beneficial and promising research programs [2].

In this research, technology fusion-based research programs are developed through systematic approaches. To understand state-of-the-art technology trend, technology push factors are investigated. For ensuring that the identified program produces useful and beneficial results, market needs are studied. This process leads to a

total of 124 technology fusion-based research program candidates. The candidates are refined and reduced into 36 research programs through survey and expert reviews. Finally, the top 10 research programs are presented after prioritizing them using various evaluation criteria.

2. THE REVIEW OF THE METHODOLOGIES FOR TECHNOLOGY STRATEGY

As previously mentioned, to succeed in developing technology fusion-based construction research plans, two major approaches are adopted in this study: 1) Technology push investigation, and 2) Market needs identification. This section provides the details of how these two approaches are used to identify the 124 candidate research programs.

2.1. Technology Push Investigation

Technology push investigation is to understand what types of technologies are pushing the industry for improved business practices. For this purpose, this study investigated academic papers, industry reports, and patents in the related fields.

The review of academic papers is an efficient method for identifying the trend of construction research and development. In this research, proceedings of ISARC (International Symposium on Automation and Robotics in Construction) and Journal of Automation in Construction from year 2000 to 2006 were reviewed to analyze the technology fusion based research trend. A total of 1,374 proceedings and journal papers were found in the area of technology fusion-based construction research and development. The 1,374 proceedings and journal papers were categorized into six areas, depending on where (in what phase of the project life cycle) the technology is used: 1) design optimization, 2) intelligent construction site, 3) procurement, 4) construction robot, 5) maintenance, and 6) the entire project lifecycle [3]. Also 46 keywords are extracted and used to produce patent maps. The database used is Aureka 9.0. United States, Japan, and European Union are the regions in which related patent information was searched. The patent search was conducted on the duration between January, 1991 and October, 2006. Patent maps were produced to make it easier to deduce the trend of research and development in the area of advanced construction technology [4].

Other interdisciplinary research programs were benchmarked, such as FIATECH (Fully Integrated and Automated TECHnology) capital project technology roadmap (CPTR) and CII (Construction Industry Institute) needs assessment. The FIATECH CPTR investigated 9 critical elements of advanced technologies across all phases of construction project lifecycle [5]. CII needs assessment showed the needs of owner, construction, and architecture/engineering companies to discover important research projects. CII, then, categorized the needs into construction, engineering, finance/risk, lifecycle, operation and workforce. Going through these processes, CII could reveal the tendency of the changes in construction industry, and suggest the plan for facing those challenges [6].

2.2. Market Needs Identification

Market needs are identified based on expert panel discussion, questionnaire-based survey, and committee reviews, in order to extract a range of technologies that are needed in the present and future construction industry. To figure out the technology needs of construction market, a 17-member panel was organized. The experts in industry and academia formed the 17-member panel. They discussed the overall technology demand of construction industry, to deduce 18 market-driven technology needs.

A questionnaire-based survey was conducted, involving 340 experts, who work in academia, industry, and government supported research institutes. The questionnaire was originally distributed to a total of 2,472 people, obtaining the 14% of response rate. The survey questionnaire consists of three major parts. First, the survey asked how much impact new technologies would have on the future construction industry. Second, the market needs identified from the expert panel discussion were asked to be evaluated. Finally, each survey respondent was asked to suggest research programs considered to be the most important and urgent for dealing with the challenges of construction industry. The responses to the last question, along with the technology push investigation, resulted in the total of 124 new

technology fusion-based research and development programs. The 124 programs were refined and reduced into 36 candidate programs through a committee review. The committee is composed of 27 members in academia, industry, and government organizations.

The 36 technology fusion-based research programs are also based on the vision and objectives of C4TF (Center for Technology Fusion). C4TF is an interdisciplinary research center, with the vision of a significant level of improvement in productivity, quality, and safety, through developing technology fusion-based research programs. The objectives of C4TF are: 1) fast and flawless design, 2) un-manned construction, 3) on-time construction, 4) extended life span of facility, 5) high-performance construction materials, and 6) multi-skilled high-level human resources. There are 9 distinctive features of the developed 36 technology fusion-based research programs: 1) sustainability, 2) integration, 3) visualization, 4) automation, 5) optimization, 6) intelligence, 7) network, 8) high performance, and 9) high efficiency.

Table 1 Six Departments of Technology Programs

No.	Department	No. of Programs
1	Plan/Design	5
2	Construction Robot	7
3	Modularization	5
4	Construction Management	6
5	Maintenance Management	7
6	New Materials	6
Total		36

The 36 technology fusion-based research programs are categorized into six departments: 1) plan/design, 2) construction robot, 3) modularization, 4) construction management, 5) maintenance management, and 6) new material. Each department has on average 6 research programs.

Each technology fusion-based program has RFP (Request For Proposal) which includes a technology description and a TRM (Technology Road Map). The RFP also includes the necessity and objective of the research program. Five or ten years of TRM is in the RFP, so each element technology has its own schedule as to when and what need to be done to achieve the technology fusion-based research program.

2.3. Prioritizing Technology Fusion-based Research Program

The Analytic Hierarchy Process (AHP) analysis was used for prioritizing the technology fusion-based research programs. The AHP analysis is a methodology of pairwise comparison for reflecting knowledge and experience of evaluators. In this research, 21 construction experts derived the criteria of evaluation and 298 experts evaluated the 36 candidate programs.

3. THE ANALYSIS OF RESEARCH RESULT

The evaluation criteria of AHP are: 1) possibility of creating new market, 2) current market needs, 3) policy, 4) goal achievement, and 5) potential market size. Possibility of creating new market is the degree of possibilities that the developed technologies are able to create new market or heavily change existing markets. Market needs is the expected demands of the developed technologies. Policy is a level of conformance with government policies for the welfare of the general public. Goal achievement is the possibility of accomplishing the technology development goal within the specified research period. Market size is the current market where the new technology can be sold at a good price. Each criterion was derived by 21 construction experts. The AHP result is indicated at Table 2.

The highest criterion is the possibility of creating new market, and it obtains a 0.295 AHP score. Market needs and policy obtains 0.271 and 0.161, respectively. Size of market obtains a 0.122 AHP score.

After deriving five criteria, 298 construction and other construction related experts out of 2,096 people (14.2%) took part in the questionnaire-

based survey for prioritizing the 36 candidate programs. Fig. 1 shows the organizations that the 298 survey respondents are affiliated with at the time of response. Experts from construction company accounts for biggest portion (64%). Research institutes and academia account for 30% and 21%, respectively.

Table 2 Criteria of the AHP Analysis

No.	Criteria	AHP score
1	Possibility of Creating New Market	0.295
2	Market Needs	0.271
3	Policy	0.161
4	Goal Achievement	0.152
5	Size of Market	0.122
Total		1.000

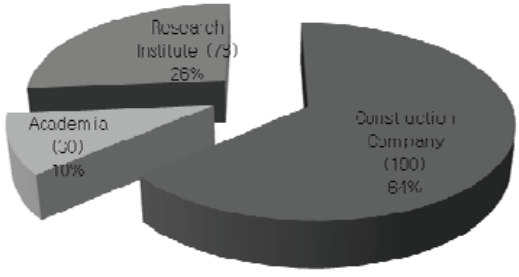


Figure 1 Affiliation of Respondents

Table 3 shows the top 10 research programs based on the AHP survey result, with the highest total score given to "Real-time Monitoring-based Construction Safety and Disaster Prevention/Management System" (0.245).

4. CONCLUSIONS

The systematic procedure has been introduced to identify promising technology fusion-based construction research programs, based on technology push investigation and market needs identification. The identified research programs were prioritized through the AHP analysis. To verify the technical feasibility of the research programs, pilot research are planned. In addition, an economic analysis is necessary to validate the developed research programs.

Table 3 Top 10 Technology Programs

No.	Program Name	Total
1	Real-time Monitoring-based Construction Safety and Disaster Prevention/Management System	0.245
2	Intelligence Lifeline Facility Management System	0.235
3	Advanced Sensor-based Real-time Project Management System	0.234
4	Integrated Asset Life-Cycle Management Program	0.228
4	Developing Advanced High Performance/ High Durability Eco-friendly Construction Finishing Material	0.228
6	Bridge Prefab and Automated Construction for Rapid Urban Construction	0.226
7	High-Performance Whole Building Management System	0.223
8	Developing Advanced High Performance Window Material for Future Housing	0.223
9	Developing 3-D Geotechnical Design System Using Advanced Radar Technology and Integrated Geotechnical Information Database	0.223
10	Developing Thermal Energy Adjustable Structural Window System	0.222

5. ACKNOWLEDGMENTS

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ANALYZING CHARACTERISTICS OF DESIGN BUILD DELIVERY SYSTEM IN KOREA

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ABSTRACT

Design build (DB) is a construction project delivery system which has become one of the favored ones and the growth of DB by the public agencies has been steadily increasing. DB can be viewed as an evolutionary project delivery system, since DB project team members collaborate on work with each other, keep seeking cost effective and innovative alternatives that meet the construction needs of the project. Thus DB outperformed others in delivery speed, cost saving, and turnover quality. In Korea, DB projects likewise have steadily increased that it is needed to analyze characteristics of DB delivery system in Korea. For that purpose, this research would offer an analysis of characteristics of DB delivery system in Korea by investigating the public market trend, comparing DB performance to DBB, and analyzing questionnaire survey.

KEYWORDS

Delivery System, Design Build, Design Bid Build, Performance Comparison

1. INTRODUCTION

1.1 Research Background and Objectives

Design build (DB) is a construction project delivery system which has become ones of the favored ones and the growth of DB by the public agencies has been steadily increasing. Numerous studies over the years have been conducted to measure its performance. The results show DB projects to outperform design bid build (DBB) in cost, construction schedule, changes, and rework (Konchar & Sanvido 1998, CII 1998, Ibbs et al 2003). In Korea, DB was introduced in 1975 and the portion of DB project was kept about 10% until 2000 in the public sector. Since then, DB projects have steadily increased, with 26% of public projects being procured by DB in 2005.

Together with quantitative expansion, the Korean government made an effort, such as ‘A Plan for Increasing DB Projects (1996)’, and ‘A Plan for Increasing Efficiency of Public Project (1999)’ for making DB a better system in Korea. Since the plans only consist of descriptions of project scale and a list of project types for choosing the delivery system, they cannot avoid critique (Seo 2003).

The research literature of DB in Korea is drawn on for the suggestions of problems of objectivity of bidding method, confidence in evaluation, high cost for proposal (Kim 2004), high contract price, and exclusive possession of major contractors in market (Lee 2004). However, previous research had been analyzed fragmentarily based on the present state without analysis of empirical data and performance. Consequently, they have limitations of diagnosing present state, tracing the origin, and thus they suggest short term prerequisites for improving.

Therefore, the purpose of this research is to offer a result of analyzing characteristics of DB delivery system in Korea by comparing performance to pervious research and conducting a survey for suggesting prerequisites for improvement. This research would make a contribution to construction industry as a means of being the basis of systematical performance analysis, and developing delivery system in Korea.

1.2. Problem Statement

Despite DB projects in Korea have steadily increased, only a few contractors join the bidding, before prequalification and several big contractors are successful.

1.3. Research Scope and Process

In Korea, DB is generally called Turn Key, but there is a difference. DB means that contractors would be responsible for design and construction, but Turn- Key means that contractors would be responsible not only for design and constructions but also for equipping the facility to be ready to run. So, in this paper, the word 'DB' is used for analyzing characteristics design build delivery system, especially in the public sector, in Korea. Overall process of this research is as below.

(1) Define delivery systems and understand general characteristics of DB from literature review.

(2) Investigate the public market trend, compare performance comparison between DB and DBB and conduct a survey for analyzing the present feature of DB in Korea

(3) Analyze characteristics of DB by comparing between result of above mentioned and previous research.

(4) Provide practical a guide to assist owner and suggest prerequisites for improving DB delivery system

2. BACKGROUND

2.1. Delivery System

There are several definitions of delivery system. In this paper delivery system is a system that regulate the roles and responsibilities of planning, design, construction, operation and maintenance to participants. Thus, three principle delivery systems are used, DBB, DB, and construction management (CM), according to making up the roles and responsibilities of architect, contractor, and construction manager one another.

2.2. Design Build (DB) Delivery System

DB is an outgrowth of a project delivery system steeped in antiquity, dating as far back as the construction of the pyramids in 1596 B.C., and an industry-driven program to find a better project delivery system (Levy 2006).

Recently, the traditional DBB project has become design-bid-redesign-rebid-build project. Budget prepared by the owner often fall short of the actual cost of construction, requiring expensive redesign, making less acceptance of value engineering, and delaying in bringing the project on stream. Because the construction project has become mega-sized, complicated, and the level of client's requests is raised.

Searching for a better project delivery system is a continual process. The construction manager (CM) and design build (DB) concept presents another alternative to the conventional DBB method. Especially, DB can be viewed as an evolutionary project delivery system, since DB project team members collaborate on work with each other, keep seeking cost effective and innovative alternatives that meet the construction needs of the project. Thus DB outperformed others in delivery speed, cost saving, and turnover quality. The report form U.S. Legislative Analyst's Office (LAO) presented in February 2005 compared two primary construction delivery systems-DBB and DB (Table 1).

Table 1 Construction Delivery Processes: Pros and Cons. [Courtesy: Legislative Analyst's Office (LAO), State of California]

Advantages	Disadvantages
DBB	
- Building is fully defined - Competitive bidding results in lowest cost - Relative ease of assuring quality control - Objective contract award - Good access for small contractors	- Agency gets involved in conflicts and disputes - Builder not involved in design process - May be slower - Price uncertain until construction bid is received - Agency may need more technical staff
DB	
- Price certainty - Agency may avoid conflicts and disputes - Builder involved in design process - Faster project delivery - Agency needs less technical staff	- Limited assurance of quality control - Subjective contract award - Limited access for small contractors

In 2002, a report prepared for The National Institute of Science and Technology (NIST) and the Construction Industry Institute (CII), in conjunction with ongoing research by the Building and Fire Research Laboratory (BFRL) can be noted briefly:

- DB projects are four times larger than DBB in terms of project cost
- Public sector projects make less use of DB projects than private sector projects
- Industrial projects made greater user of DB than building projects in the residential or commercial sector
- Overall, owner submitted DB projects outperform DB build projects in cost, construction schedule, change, and rework.

3. INVESTIGATE THE MARKET TREND

3.1. DB Projects are Steadily Increasing

There is a striking change of increasing DB projects in Korea recently, in the public sector. From 1975, the year DB was introduced, to 1994, the average DB projects per year were at most 7 projects. Total DB projects were merely 107 projects during these 17 years. Until the year end of the year 2000 the projects using DB occupied only about 10%, and since then, the growth of DB by the public agencies have been steadily increasing. In 2005, projects worth about $13 billion, 26% of public projects, were delivered using DB. (Figure 1)

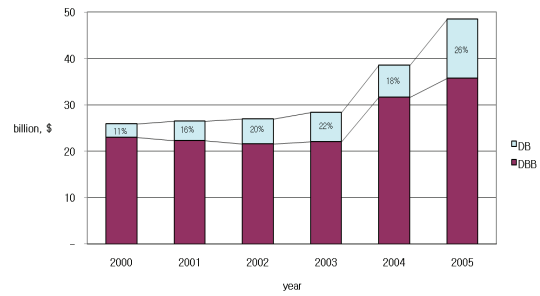


Figure 1 Overview of DB Project Increasing (Public Sector)

3.2 Only a Few Bidders Submit a RFP Responding

Generally, the more DB projects in the market, the more bidders are joined to the tender. However, in Korea, only a few bidders participate in DB bidding. In the early 1990's, only 3 to 5 bidders joined DB projects, and in the late 1990's, this did not exceeding 3 attendants. For the last 3 years, the number of DB bidders, that have submitted a request for proposal (RFP), was below 3. In contrast to DB, the mean bidders of DBB project were 355~536. (Table 2)

Table 2 Overview of Number of Mean DB Bidder

	2004		2005		Oct. 2006	
	DB	DBB	DB	DBB	DB	DBB
Bid attendant	2.5	355	2.5	396	2.5	536

3.3 Only Several Big Contractors are Successful

Although DB projects by the public agencies have been steadily increasing, the diversity of contractors, which were successful in DB bidding, has not altered for the better. During recent years, the top 6 contractors account for ver 67% of public DB projects exclusively. (Table 3)

Table 3 Overview of Award DB Contractors

year	2002	2003	2004	2005
% of the top 6 contractors in successful DB bidding	79.9	81.7	67.3	67.8

4. ANALYZING CHARACTERISTICS OF DB IN KOREA

4.1 Comparison of Delivery System Performance

4.1.1 Factors for comparison

For comparison of delivery system performance, many kinds of factors such as cost change, contract price, cost growth, unit cost, intensity, construction/procurement speed, construction schedule growth, unit construction day, schedule change, productivity, quality, and claims are putted these to good used (Ibbs et al 2003, Konchar & Sanvido 1998, Hyun et al. 2000).

Similarly, this paper sets limits to cost growth, budget growth, construction schedule growth, and owner satisfaction for comparing delivery performance between just DB and DBB projects. There is a cost limit that has been provided to bidders before biding, they have to tender less than this budget, and most of public projects have been completed within the budget, so budget growth carry an important meaning in Korea. Thus, cost, budget, and construction schedule growth could be measured by empirical 19 project data (6 are DB, and 13 are DBB), owner satisfaction could be measured from questionnaire survey.

(1) Cost

Cost growth (%) = [(final cost – contract price) /contract price] *100

Budget growth (%) = (final cost / initial budget)*100

(2) Construction schedule

Construction schedule growth (%) = [(total time used – initial contract time)/ initial contract time]

(3) Quality

Owner satisfaction: taken by owners, was defined as the degree to which the facility met expected facility requirement.

4.1.2 Overview of empirical project data

There are 6 DB, and 13 DBB building and road projects 2000 to 2007 that were chosen for comparing performance, similar to a previous research done by NIST in 2002, In Korea DB projects are at least two times larger than DBB in term of project cost (Table 4).

Table 4 Overview of Empirical Project Data

	project	Initiate date	Scheduled date	Budget($)	contract price($)
DB	A	5-Jan-02	4-May-04	37,726,799	35,795,187
	C	29-Dec-00	28-Dec-02	44,214,870	35,491,276
	D	30-Aug-04	29-Aug-06	46,154,663	40,076,094
	E	16-May-01	15-Mar-03	27,613,721	24,543,075
	F	17-Dec-03	31-Oct-04	13,562,282	11,650,000
	G	24-Oct-05	15-Jun-07	13,000,000	9,295,000
DBB	H	21-Jun-04	1-Sep-05	2,322,320	2,014,845
	I	22-Nov-02	22-Mar-04	3,459,741	3,001,325
	J	22-Jun-04	20-Aug-05	2,328,041	2,019,576
	L	24-Dec-02	31-Dec-03	3,384,210	2,936,141
	M	10-Jun-04	18-Jul-05	1,710,068	1,485,707
	N	30-Dec-04	18-Aug-06	13,611,326	11,708,463
	O	8-Jan-01	19-Jun-02	9,264,345	8,089,626
	P	30-Dec-04	13-Jan-07	20,109,765	16,998,784
	Q	21-Nov-03	31-Dec-04	8,297,900	6,833,321
	R	4-Oct-04	31-Jan-06	5,855,092	5,032,452
	S	19-May-04	10-Jul-05	5,405,525	4,689,293
	T	30-Dec-02	27-Apr-04	6,953,173	5,923,408
	U	20-Jun-01	11-Nov-02	7,313,463	6,278,608

4.1.3 Results of performance comparison

There is not a significant difference in performance between DB and DBB; DB median Cost growth is 4.04%, DBB is 3.73%. DB median budget growth is 88%, DBB is 89.21%. And it was also found that both delivery systems were completed within the initial budget.

However DB was found to have the greatest construction schedule growth at 14.62%, followed by the DBB approach at 8.92%. The reason why

median construction schedule growth of DB project was high was that DB contractors in Korea, government permissions in the construction stage, moreover DB projects were conducted short pre-construction preparing such as site survey, preliminary examination, and etc., compared with DBB projects. It was found that in owner satisfaction in quality between DB and DBB, which was measured by survey similar or DB is slightly better than DBB.

4.1.4 Analyzing

Over the years, many researches, especially in U.S., have been conducted to gauge and compare the performance of DB delivery system. One such previous research by Konchar & Sanvido (1998) looked at U.S. 351 building projects in order to compare DB, DBB, and CM delivery systems. That research showed that generally DB projects outperformed the others in cost, schedule, and quality. CII (1998)'s report had the same result. As well as, Ibbs et al. (2003) which searched effective project delivery systems to maximize project performance by analyzing 67 global construction project from CII database. As a result, DB is most effective for shortening schedule.

Hyun et al. (2000) analyzed and compared delivery performances, particularly DB and DBB, concerning schedule, cost, quality, and claim of 33 projects procured by office of Seoul. In the case of road and building project among this research, DB is outperformed DBB in quality, but in savings of cost and construction schedule, DBB was better than DB. However, result of delivery system performance comparison in this research is not similar to previous. There is no great difference in cost, DBB is great in construction schedule, and DB is similar or slightly great in quality. (Table 5)

Table 5 Comparison with Previous Research

	cost		schedule	quality
	cost growth	budget growth	schedule growth	owner satisfaction
Konchar & Sanvido (1998)	DB<DBB	-	DB<DBB (complex office) DB>DBB (light industrial)	DB>DBB
CII(1998)	DB<DBB 5.2%	-	DB<DBB 11.4%	-
This research	DB>DBB 0.67%	DB<DBB 1.21%	DB>DBB 6.33%	DB≥DBB

4.2 Questionnaire Survey

4.2.1 Questionnaire organization

The questionnaire was composed of three phases, the first phase is about respondent profile, the second phase about respondent's awareness of characteristics of DB in Korea, and the third was about the cause of those kinds of characteristics.

4.2.2 Survey respondents

Over 41 surveys were conducted with 13 public owners and 28 contractors (and architects) to identify underlying causes of the above-mentioned phenomenon in DB. Among survey respondents, 69% out of owners had working experience in less than 3 DB projects, 32% of contractors had less than 3, and 46% out of contractors had experience of more than 9 DB projects.

4.2.3 Result of survey

(1) Respondent profile

41 surveys were conducted from 13 owners, of which 85% of them had a career in construction for over 10 years, and 28 contractors, all of whom had over 15years of experienced as professionals in construction. In particular, respondent's experience of DB project were: 69% of owners had less than 3 DB projects experience, 23% had 3 to 5, 8% had 6 to 8, and none of the owner respondents had over 9; 32% of contractor had less than 3, 14% had 3 to 5, 7% had 6 to 8, and 46% had more than 9 DB project experience. Weighted mean number of DB project experience of survey responding for contractors was 8.25 and for the public owner 3.15 projects. Career length in the construction industry of contractors was over 16years, and the public owner is 13.31 years, on average.

It was found that public owners had not sufficient DB project experience not only for their career but also for contractors had, relatively.

(2) Respondent's awareness of characteristics of DB in Korea

of expecting cost saving; contractor's answer was not different from owner's; 47% of contractor respondents expected high quality, 28% of contractors expected timesaving, and 21% expected cost saving. Consequently, the first.

advantage in DB is high quality, the second is timesaving, and they did not particularly count on cost saving in DB projects

Survey about the basis of that judgment, which could be relied on their own experience, or successful case of other countries, or information from expert, or etc., was conducted: only 46% of owner answered that judgment was the based on their own experience, 23% answered successful case of other countries, and 31% answered information from expert. In other word, it was found that over half of the owners considered that DB delivery system is better than DBB not form owner's experience but from other countries' successful case or expert opinion. On the other hand, 74% of contractor answered that was based on their own experience, merely 7% answered successful case of other countries, and 15% answered information form expert.

(3) The causes of characteristics of DB in Korea

58.8% of the respondents cited the high cost of responding RFP as the limiting factor keeping only a few construction companies that are able to take high risks from bidding in a DB project. In Korea,

a company cannot be responsible for both construction and design. So, the DB team has to be made for attending DB bidding between construction company and design firm, and besides, generally, construction company takes responsible for cost of preparing bid. It was an answer that

54.2% of respondents thought that the influence between the design input/specifications and design innovation was that the more the design input/prescriptive specifications there was, the bigger the innovation in design. And 55% responded that the design input and specifications at this point in time had to be decreased.

4.2.4 Analyzing

It has identified that DB is great in performance in cost saving, timesaving and quality by previous research. Whereas, Significant differences between that of Korea and the others are founded. It is a result of performance comparison that DB project was distinguished for quality; however, there is not enough of a difference for cost saving and timesaving in Korea. Nevertheless, DB projects are steadily increasing since past 5 years ago, because the public owner seemed to look forward to for DB delivery system being exceeding in performance. (Table 6)

Table 6 Answer About Causes of DB Characteristics in Korea

	Owner	Contractor	Total
1. The reason why a few bidders submit a RFP responding to a DB project			
Only big design company can make drawing for winning	53.8%	15.8%	25.5%
High cost of responding RFP limits construction company which can take high risk	30.8%	68.4%	58.8%
All together above mentioned	15.4%	15.8%	15.7%
2. The reason why cost for responding RFP in DB is high			
Because of overburden request for proposal	76.9%	57.6%	63.0%
Because of illegal activity	23.1%	42.4%	37.0%
3. The reason why several big contractors were successful in DB			
Because High cost for responding RFP but not sufficient compensation made a few bidder of RFP responding	53.8%	34.5%	40.5%
Not good diversity of successful DB contractor	15.4%	37.9%	31.0%
Big contractors have excellence in design and construction	30.8%	27.6%	28.6%
4. The influence between the design input/specifications and design innovation			
the more the design input/prescriptive specifications the less design innovation	69.2%	42.9%	51.2%
the more the design input/prescriptive specifications the more design innovation	30.8%	39.3%	36.6%
no influence	0.0%	17.9%	12.2%
5.The design input and specifications at this point in time			
it will be decreased	46.2%	59.3%	55.0%
it will be continued the present level of detail	23.1%	22.2%	22.5%
it will be increased	30.8%	18.5%	22.5%

Table 7 Comprehensive Performance Comparison

		cost saving	timesaving	quality
In Korea	Performance comparison	inappreciable	DB<DBB	DB≥DBB
	Survey result	DB>DBB	DB>DBB	DB≥DBB
	Hyun et al.(2000)	DB<DBB	DB<DBB	DB≥DBB
Previous research about Other countries		DB>DBB	DB>DBB	DB>DBB

5. CONCLUSION

It is a problem that lack of diversity of responding. RFP brings about a lack of diversity of successful DB teams of construction and design companies. For analyzing characteristics of DB, an empirical comparison of delivery system performance 19 projects and a questionnaire survey were used. Based on these results, the characteristics of DB delivery system in Korea were analyzedIt is conformed that DB delivery system in Korea was used for relatively bigger project than DBB like previous research of NIST (2002) et al. Whereas, DB project was distinguished in quality but there is not enough of a difference in cost saving and

timesaving in Korea. However, the public owner had a confidence that DB delivery system would be excellent without enough experience or information which is caused of absence of performance measure or analysis result. Therefore, performance measure system should be set up for analyzing and developing construction delivery system.

The cause of a few bidders submit a RFP responding to a DB project was high cost of responding RFP limits DB companies which can take high risk. The reason why several big contractors were successful in DB bidding is because of not only high cost for responding RFP but not sufficient compensation made a few bidder of RFP responding, but also not good diversity of successful DB contractors. Consequently, prescriptive specifications and overburdened RFP made high cost for responding in DB made only a few bidders submit a RFP responding and several big contractors were successful. High cost for responding DB RFP is general phenomenon in DB delivery system over the countries. Thus, it is demanded that change form overburdened prescriptive specifications of design, which permit fewer options to submitting bid, to performance specification allow a smart firm more freedom in design.

It must be noted, however, that this study was carried out using limited data, and thus there is a need for a continued study that analyzes of a wider range of data whilst taking into perspective the culture of construction

6. ACKNOWLEDGMENTS

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PERFORMANCE MANAGEMENT METHOD FOR CONSTRUCTION COMPANIES

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ABSTRACT

Many companies have managed their business performance in order to achieve their enterprise purpose. Performance management which applied concept of BSC (Balanced Scorecard) is widely used all over the world. In the construction industry, BSC-based performance management is currently introduced with needs of balanced performance evaluation. However, most companies actually have intermediate level of adapting BSC. It is important to understand its process or and structure. Therefore, this paper is focused on making performance management process and defining each phase of it. In addition, the framework is established with putting them together and simulation is conducted for practical use. With developing performance process in construction, the construction companies are supposed to detect the deficiencies of the current performance management systems and take some opportunity to be helped for supporting their decision-making. In conclusion, this paper will provide the construction industry with the opportunities to enhance the values of performance management system and construction application.

KEYWORDS

Performance Management, Balanced Scorecard, Data Warehouse, OLAP, Monitoring, Search System

1. INTRODUCTION

In General, the company pursues multi-dimensional goals in terms of benefit, development, and flexibility. Flexibility means the balance between competitive objectives, decides the importance of the goals objectively and relatively. A number of companies have managed to make individual goals be coincident with organizational goals in order to maximize effectiveness against the crisis: rapidly changing business environment. To encounter this change, companies have started to bring in Performance Management, in order to accomplish organizational goals, to enhance their competitive power in the marketplace at the same time. Such effort has been continued from the traditional financial measures to Balanced Scorecard (BSC) developed by Robert Kaplan and David Norton in 1992, and still great numbers of research are on the progress. Especially, BSC performance management is in the spotlight nowadays and widely used in many companies in real.

BSC is consisted of objectives, measures, targets, and initiatives in terms of four perspectives, financial, customer, internal business processes, and learning and growth. By using BSC, we can evaluate financial and non-financial performance at the same time. Recognizing and overcoming deficiencies of previous management approaches that used to focus on the financial performance only, BSC provides 'balanced evaluation' to adjust the strategies and policies of the company.

Construction Company conducts a number of projects at a time. In addition, several companies and other groups that concerned with the business usually participate in the project contemporarily. Due to it's limitation in nature, it is complicated to act performance management in the building industry area (Yu et al, 2004). Therefore, most of the building companies have depended on financial measures (Kagioglou et al, 2001). Acknowledging the lack of balanced evaluation and prescription of the company, major companies started to bring in the balanced scorecard to check their strength and weakness. However, construction companies are still left to be ignorant of the importance of the management using BSC. It is strongly recommended to inform the process and the system of BSC in order to maintain successful performance management.

In this research, we are going to define the process of the management, and introduce the details of each step on the process. Next, we establish framework that can lead to build a system for evaluation, and guide you to understand management steps in general. Finally, we will carry out a simulation to encourage further understanding of the actual performance management.

2. LITERATURE REVIEW

2.1 Example of Performance Management Process

A performance management is a systematic approach to improve their goals through an ongoing process of establishing strategic performance objectives; measuring performance; collecting; analyzing; reviewing; reporting performance data; and using that data (PBM SIG, 2001). In DTI of UK, they divided the process for successful application of KPIs into 7 steps shown in figure 1 and the process has applied for measuring their goals.

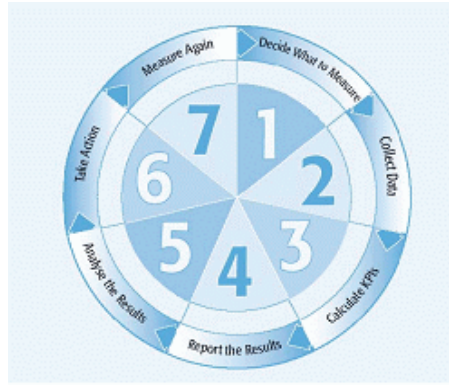


Figure 1 7 Basic Steps to the Use of KPIs in DTI

2.2 Example of Performance Management in Construction Industry (1)

Construction Industry Institute (CII) has created database from more than 1,000 projects collected from their union companies since 1996. This system gathers related data measured as five perspectives shown in table 1 from participants and KPIs. The system supplies the circumstance to companies such as benchmarking or comparing with sample project.

Table 1 Result Standard of CII

CII Performance Measurement System	Safety
	- RI.R - LW.C.I.R - Zero Recordable - Zero Lost Workdays
Cost	Change
- Cost Growth - Budget Factor - Cost Factor	- Change Cost Factor - Change Schedule Factor
Schedule	Rework
- Schedule Growth - Duration - Schedule Factor - Duration Factor	- Rework Cost Factor - Rework Schedule Factor

2.3 Example of Performance Management in Construction Industry (2)

Department of the Environment, Transport and the Regions (DETR) from UK, they decide Key Performance Indicators (KPIs) for measuring their performance at the level of project and enterprise. KPIs are divided into 7 groups, and each group has indicators in detail. And each Indicator is consisted of Headline Indicators (HI), Operational Indicators (OI), and Diagnostic Indicators (DI) through their level. The cube, combined with time and supply chain dimensions, is created for multi-dimensional analysis. It is an elastic framework for making KPIs and applying in need.

2.4 Example of Conceptual Framework of Performance Management in Construction Industry

Kagioglou (2001) suggested concept framework according to measurement of performance in construction industry. Basically, his framework is based on the six perspectives, added perspectives of project and supplier from previous perspectives, and decides what is to be aimed and measure items of each perspective. It has been made to input the measured result and relative importance. It can get information for vision and strategy of enterprise through every perspective, measures items using input data and is able to analyze performance based on measured result within matrix.

3. FIVE PHASE OF PERFORMANCE MANAGEMENT PROCESS

3.1 Measure

Measuring phase defines the necessary perspectives for its performance management based on a concept of BSC and sets the objectives of performance. After that step, it deducts success factors, sets the target of performance and measures data with assessment of measurable index. It can add or remove new perspective in need from a criterion of standard perspectives. It is necessary to consider their weight because there would be a difference of importance among perspectives.

3.2 Store

In storing phase, it is a step for loading performance data into Data Warehouse (DW) and it defines fact table which contains measured data and dimension table including descriptive information about fact, and it sets the link for every table. From that, performance data schema is embodied. Data accumulated in DW has two kinds that which are measured data and converted data through extracting, refining stored data in operating system.

3.3 Analyze

In analyzing phase, it is a step which makes multidimensional analysis applying OLAP with performance and related data stored in DW. Most of the dimensions have the hierarchical structure. It enables to analyze the data of each level which is required by users. Next, the cube is made, after classifying hierarchical structure of dimension and setting level. The method of cube is decided according to purpose and situation of their analysis and it analyzes with slicing and dicing by preference of users.

3.4 Report

It is a phase of creating appropriate pages from result of previous step using table and picture without extra programming. In this step, user analyzes information through interaction with system and it displays its report to screen. When analyzing, xml formatted data which has been extracted simple information are stored in database of searching system going to be used in next step.

3.5 Use

This phase is used for solving problem and supporting decision-making with result from analyzed data. In case of application, by using xml, it offers similar contents of searching result as an advertisement from searching system, and tools which offer comparable display that they can get more data and enables their role for helping reasonable decision making.

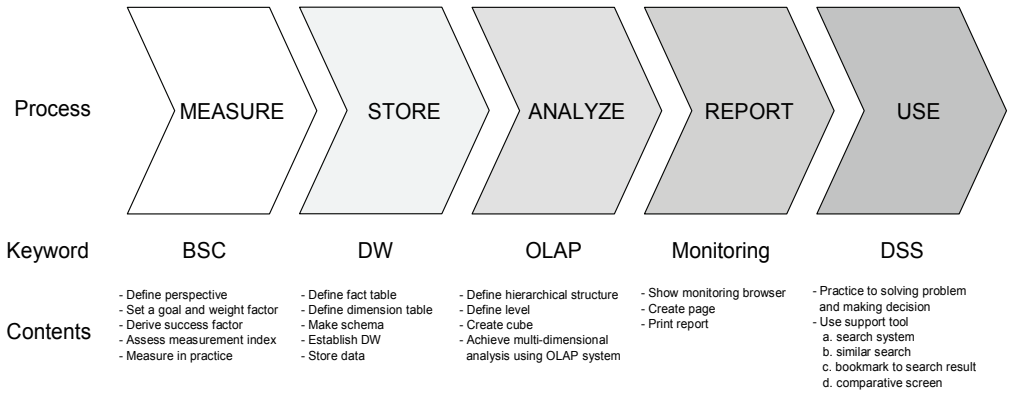


Figure 2 Performance Management Process

4. FRAMEWORK OF PERFORMANCE MANAGEMENT

Performance management framework is developed as shown in figure 3.

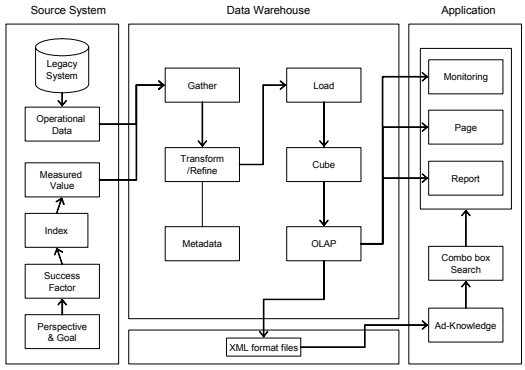


Figure 3 Performance Management Framework

4.1 Source System

Source system provides data, which are stored in data warehouse. It is divided into business system and measurement system. Business system. includes Enterprise Resources Planning (ERP) system, sales system, technology support system, research and development system headed by project management information system (PMIS). Measurement system is composed of several items, which are strategic goal, performance index, and measurement plan and result. Source system plays a role in inputting and saving measurement result into system on the measurement phase and selecting and preparing data needed for formation of fact table and dimension table on the store phase

4.2 Data Warehouse

It is important 'How to analyze and use the measured data?' as well as 'What is measured?' in management. Data warehouse is given a great deal of weight on the framework and the foundation of total system. Selected data in business system, first, is stored to DW. For that, procedure of extracting, transferring and loading (ETL) is needed. Refined data through ETL are finally stored in DW established by data schema. Next, cube is created and the table of matrix structure in order to be related between dimensions is obtained using on-line analysis processing (OLAP) tool.

4.3 Application

It presents the following applications on the framework, for providing answer of question about how to use analysis result to end-users, including experts. It shows analysis results along the several methods because users' access is restricted in the view of the composition of a screen and practical use in analysis phase. Thus, users can be experienced in report format used mainly from the past to the present, monitoring form on the screen, and web page to see on the internet. However, for the more positive performance management, method convert-ing performance results to knowledge using IT technology is selected. The method is that summary pages with xml structure

are created, making of web page simultaneously and those are stored into the new database for search. This provides end-users with advertisement of similar contents, when they search for performance analysis results.

5. SIMULATION OF PERFORMANCE MANAGEMENT

5.1 Source System

In simulation, using advice of experts and literature review, it has decided its contents fits for every perspective with a concept of BSC shown in table 2. About planning data and result data, it made to get the estimated analysis results by inputting intended data, not real data.

Table 2 Performance Index in Performance Management

Perspective	Goal	Index	Plan	Result
Financial	Maximum benefits	achievement ratio of sales	100% ($86,730)	109.2% ($94,680)
	Reduce the term of work	the days required or placing concrete	4days	4.4days
Customer	Image improvement	rate of solutions of public grievance	100%	100%
		rate of volunteer activity around the project site	100%	95%
	customer satisfaction	rate of answer in 1:1 internet service	100%	80%
Internal process	Strengthen achievement ability of work	achievement ratio of schedule	100%	98%
	Safety	rate of conversion accident	0.35	1.26
	Environment	the number of indication though a spot check	Under 3	3
	Quality	quality level	Level 3	Level 3
Innovation and learning	Strengthen capability	amount of human resources	10	10
		the number of sharing knowledge	30	35
		rate of education and training	100%	110%

5.2 Data Warehouse

In order to saving data into data warehouse, the matrix of data warehouse has been established. First, define fact table and dimension table shown in figure 4. Next, it makes data schema which sets relationship of each table. Each table makes data schema for setting their relationship, looking figure 4, you can see many of dimension tables are linked with fact table as their middle and database is made from those tables. In simulation, selected data in business system (summary of project, work process, activity, material, manager and subcontract) has been stored by method of ETL under actual database. Cubes are manufactured referring data schema for real data analyzing. However, relate to the fact of fact table every dimension don't have meaning so hyper cube method is used, than multi cube method. Hyper cube method connects dimensions related to every fact. So it can be created many cubes, not one cube. Next, it analyzes using OLAP tool and it shows performance of achievement ratio of sales in financial perspective by work process and by date.

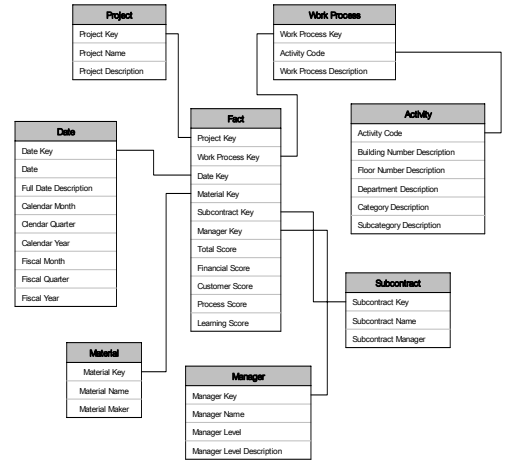


Figure 4 Data Schema Included Fact and Dimension Tables

5.3 Application

In this simulation, it is analyzed in the financial perspective and it shows as report format, monitoring and web page. With offering analyzed data like the format, it creates xml format data and stores to database for searching system. Xml format data contains basic information of project and title of query and helps to find out analyzed data with ease and detail through searching system. In simulation, it displays financial score by structural work of project A and by 1st period in 2006 using form of combo box. Similar search for that simulation shows financial score by 1st period in 2007 by brick work of project A, and financial score by 2nd period in 2006 by structural work of project A. It can help to support its decision making with re-analyzing comparable data checking above contents. Users can also bookmark

searching contents in need and show many kinds of analyzed data in one display for their convenience. Through this application, we can expect the high application rate of performance management. The final display of this application is planning to launch in web circumstance. It shows prototype of for final display in figure 5 and it is supposed to improve through more research and development.

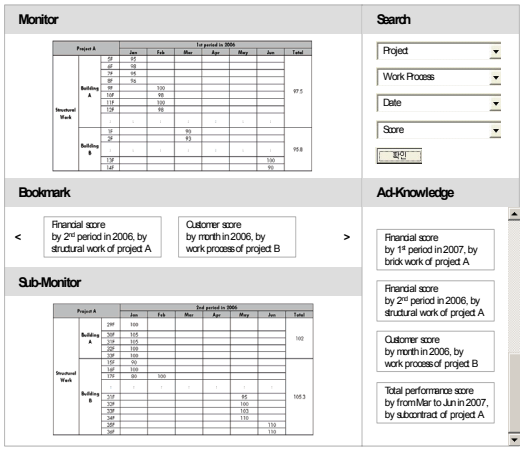


Figure 5 ProtoType of Performance Management

6. CONCLUSIONS

We focused on the positive performance management at the project level, and proposed a framework based on contents of each step in performance management process. In addition, we carried out a simulation to know how performance managements are performed at the project level.

In the suggested method, performance management process is the most important thing to be considered, and the following actions are achieved; performance indexes are measured for performance management in measuring phase and data are accumulated to one place for analyzing measured performance in store phase. Fact and several dimensions are existed and multidimensional analysis is achieved in analyzing phase and screen, page and report so as to show the result to user is provided in reporting phase. Last, objective and comparable data is obtained by a lot of tools and applications are used practically for supporting decision-making in using phase. This paper has made a contribution to definition of process and framework, and experiment of efficient performance management's possibility. However, it needs verification of actual situation with real data for practical use. Therefore, actual example applied with construction is presented and further research establishing system is required.

7. ACKNOWLEDGMENTS

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3D LOOM – AUTOMATED DESIGN AND MANUFACTURING OF TAILOR-MADE HIGH-TECH FABRICS

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ABSTRACT

Today high-tech fibres such as glass or carbon fibre are used for a wide range of applications, e.g. aviation, navigation, and even astronautics. Innovative ultra-light flexible membranes and stiff shells are utilized wherever the combination of lightweight and high rigidity is needed.

A even newer area will be the construction sector, introducing high efficiency in relation to stability, thermal insulation and of course weight for completely new levels of innovative freeform and high-tech architecture.Unfortunately nowadays' production of these materials has little relation to high-tech, but mostly to handcraft. To utilize theses materials even for cost effective applications an new way of automated and efficient manufacturing has to be developed: By bringing together latest standards of computer simulation and innovative robotics, the efficient production of mass customised high-tech fabrics can be realized.

KEYWORDS

High-Tech Fibres, Composite Materials, FEM, CAD/CAM, Robotics

1. INDUSTRIAL BACKGROUND

The invention of high tech fibres such as carbon or glass fibre has been revolution nary for various fields of engineering. Especially the industries focusing on an efficient power-to-weight-ratio (e.g. vehicle and aircraft construction) profited by these new ultra-light and rugged materials.

1.1 Types of Fibres/Composite Materials

There is a wide range of high tech fibres and composite materials available for all kinds of application, featuring very little weight combined with high stiffness, braking strength and abrasion resistance.

All are based on small extremely strong fibres, such as glass fibre or carbon fibre, as well as aramid fibres (e.g. Kevlar or Nomex).

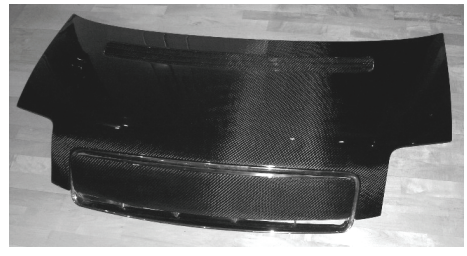


Figure 1 Lightweight Race Car Hood Made of CFRP

They can be used for two general types of applications: Flexible Membranes (e.g. clothing) and stiff shells (e.g. car parts, Fig. 1).

In the majority of cases these fibres or fabrics are combined with other materials in a composite or sandwich structure. Often Membranes are based on layers of different fibres and added foils or coatings for impregnation or UV resistance. To produce stiff shells, several layers of fabrics are

compounded with liquid plastics such as epoxy, polyester or nylon combined with hardeners (so called fibre reinforced plastics, e.g. glass fibre reinforced plastic (GRP) or carbon fibre reinforced plastic (CFRP)).

1.2 State of the Art in Manufacturing Fabrics and Composite Materials

The fibres itself as well as semi-finished products are manufactured by full automated production lines, enabling stable quality and cost effectiveness at the same time.

The final products however are mostly handcrafted as unique or limited lot production. The main reason for that is the complex handling of the materials: All composites and many membranes consist of several layers of fibres, foils or fabrics, which have to be separately glued, sewed or cast. Reinforcing the almost homogeneous components means extra layers of holohedral or pre-cut material, which have to be processed the same way.

Due to the small number of units the formwork for the composites is mostly handcrafted as well.

1.3 Possible Use of Prefabricated Fabrics in the Construction Sector

The relevance of using high tech fibres as structural component in architecture is obvious. Keen architectural design as well as the need for higher and bigger high tech structures can only be realized by using modern materials and instruments.

Stability and stiffness combined with durability were sought-after features from the beginning of construction industry, but now theses fibres can add “light-weight” as an additional value.

Self-supporting facades, freeform bearing structures or long-span membranes are only a few of the multiple applications in architecture.

2. CUSTOM-TAILORED FABRICS WITH ORIENTED FIBRES

The fabrics and semi finished products today available all have a preferably homogeneous structure to fit as much applications as possible. The fibres are either woven to a tight fabric or scattered to a more or less unoriented mesh. (e.g. CFRP and GRP; Fig. 2)

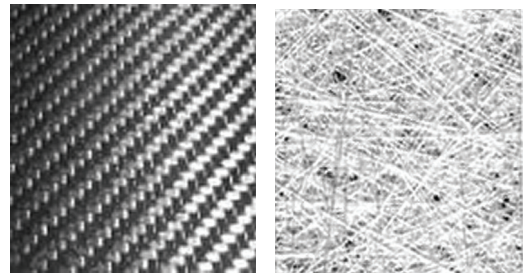


Figure 2 Conventional Orientation of Fibres (CFRP and GRP)

The tear proof fibres are structured preventative in every direction to balance every possible loading condition. This universal approach works for rather small work pieces, but realizing larger structures for the construction sector will become very inefficient by causing lots of cut-off waste and unnecessary working steps for layering etc.

2.1 FEM-Simulation

Simulations based on the finite-element method (FEM) are well proven in many engineering disciplines, such as mechanical or aeronautical engineering. It is used to solve complex structural analysis problems, incorporating for example elasticity or torsion under various load cases (Figure 3).

Architects and civil engineers started using these simulations few years ago to handle new architectural challenges by far too complex for conventional methods of static calculation.

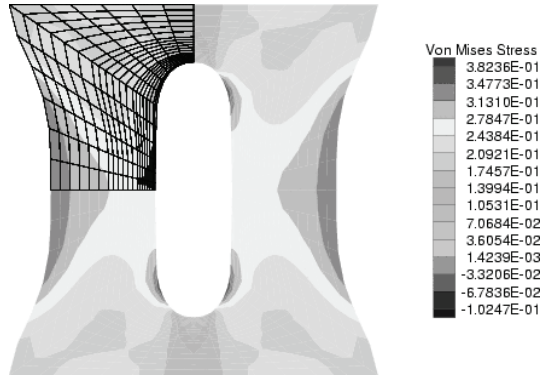


Figure 3 FEM Analysis of Structural Element

2.2 From Stress Splines to Fibres

Software using the finite element method (FEM) for structural analysis can determine exactly the progression of torque and stress for every individual application or loading condition. Translated into a mesh plot the principle stress distribution can be shown in diagram-like lines, providing the basic scheme for the run of the fibres in the fabric(Fig. 4). So instead of a homogeneous fabric or tissue (Fig 2) the amount of fibres and alignment of every single strand is defined by the results of the structural analysis.

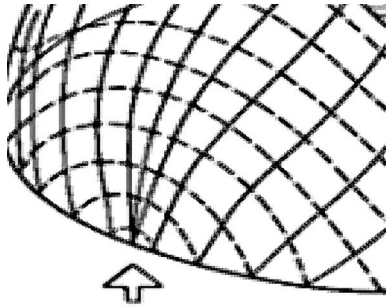


Figure 4 Simplified Scheme of Stress Splines in Cupola Segment

3. TECHNICAL IMPLEMENTATION

3.1 Link-up of CAD, FEM and CAM

The connection between Computer Aided Design (CAD), Finite Element Method (FEM) and Computer Aided Manufacturing (CAM) is well established in many industries. And even the construction sector uses the link between FEM and CAAD to analyse complex designs and structures. There is a variety of data formats supporting the exchange of information between theses different types of industrial software applications.

The new Industry Foundation Classes data model (IFC) will simplify the implementation of the needed information even more, providing a detailed and open object-oriented 3D model, which will contain every general data, for instance the layer composition and layer thickness.

The only difference is that in addition to the conventional 3D information of the component itself the results from structural analysis are implemented into the 3D data model as well, defining the precise run of fibres.

While the basic component data is mainly used for the formwork, the mesh plot of stress splines is translated almost one-to-one by the CAM manufacturing unit (Fig. 5).



Figure 5 Alignment of Membrane Fibres Based on the Stress Splines

3.2 Technical Production Setup

3.2.1 3-Axis portal with 6-axis robot

A 6-axis articulated arm robot mounted on a 3-axis portal can translate the mesh plot into a individual fabric, following the simulated tension lines with a “endless” flexible fibre. Trimming of the fibre where needed and injection or spraying of e.g. epoxy or polyester can be done during the same work step. The alignment and amount of single fibres as well as laminated layers is exactly determined by the demands of the it’s future application.

A feeder system provides endless fibres from movable coils and liquids (epoxy or resin and hardener etc.) from tanks (Fig. 6). Depending on the amount and number storage containers, the feeder system can be either mounted on the movable portal or placed separately beside the unit, supplying the robot tool via flexible tubes and ducts.

Covering with foils are additional ready-made fabrics can be realized by a second movable portal, similar to a industrial roll paper feeder.

The speed an precision of this “all-in-one” unit allows a fast and accurate production, the dimensions of the workpiece are only limited by the dimensions of the portal and assembly table.

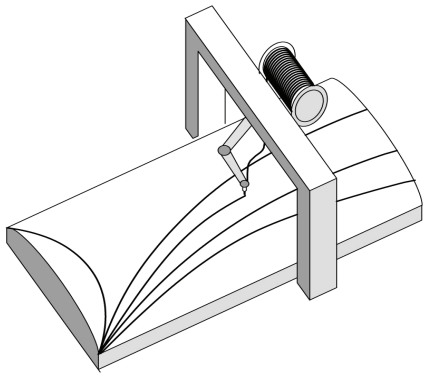


Figure 6 Scheme of Manufacturing Robot Unit

3.2.2 Formwork

Efficient automated fabric production requires a rational way of fabricating formwork as well.

The easiest way is a single-serving mold made of expanded polystyrene. Mounted on the assembly table of the robotic unit it can be processed in a similar way the fabric is manufactured later on. By establishing a milling tool for the robot or even a second robot arm, the Formwork can be millcut with the same 3D information used for the fabric as well. A non-adhesive foil plus a release agent or wax is applied on top.

A more elaborate way to create complex formwork for freeform shells and membranes is a automated formwork table. Under a tense air filled cushion a grid of free addressable pneumatic punches is installed, defining designated points of the form in a 3-axis coordinate system The cushion provides a flush non-adhesive surface and smoothes the 3D Form provided by the punches. Once again a release agent separates mold and workpiece. Vacuum will help to fix the fabric.

4. CONCLUSION

By using this modern technologies of simulation and manufacturing it is possible to produce tailor-made high efficient fabrics for flexible wide span membranes as well as highly rugged and stiff 2D and 3D components like domes or shells with outstanding capacities. Using a seamless chain from FEM simulation to automated CAM production the fabrics will be even more affordable.

Setting a new standard in composite production, this development may be compared to the gain of efficiency when hand-looms had been replaced by automatic looms during 19th century industrialization.

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AUTOMATIC PROCESSING OF NATURAL FIBRES FOR INDUSTRIAL MANUFACTURING OF FIBRE REINFORCED EARTH PLASTERS

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ABSTRACT

A European research activity under title Innovative production of high quality indoor earth plaster by adding natural fibre is realizing new industrial processes for manufacturing traditional building materials. Earth plaster reinforced by natural fibres is a healthy alternative to the use of cement, lime or gypsum based plasters still producing almost the same treatment and strength properties. In comparison to the common earth plasters additives like straw, hemp or lax, natural fibre binds the mineral components symmetrically in all directions producing an isotropic strength property. The problem is now how to automate the fibre treatment process softly enough to keep fibre structure undamaged during different process phases. Industrial process consists of unit processes for receiving of raw material, separation of fibres, and separation of seeds and bones, volumetric weighing of fibre and finally packing of the fibres in bags, whose size is compatible with the batch size in the plaster production plant. The development process of the fibre handling line has been realized in two steps. The first one includes a set of small-scale laboratory tests of the unit processes as separated and the second one the design and build-up of a pilot plant in a scale, which represents a full production line capable of small production of fibres for earth plasters to be used in limited number of demonstration houses. The experiences of these developments will be utilized later in the design and delivery of a full-scale mass production plant for the fast growing European plaster markets.

KEYWORDS

Plaster Composites, Fibre Processing, Traditional Building Materials

1. INTRODUCTION

People spend some 95 percent of their time indoors, at home, the office, in schools and shopping. It is no secret anymore that buildings – especially modern housing – can and do make people sick. This phenomenon has been studied for at least 20 years. The list of potential indoor pollutants and effects of low-level electromagnetic radiation is growing longer each year. All this causes a multitude of body problems such as headaches, asthma, allergies, hormone disorders and even cancer [1]. It has been found out that natural Earth plaster can absorb pollutants and odours from the air:

Pollutants, such as cigarette smoke, and odours in the air are tied to the moisture in the air and filtered out when absorbed by the earth. Health wise, this cleansing ability of clay is a further huge advantage of earth building. Earth plaster has also other positive properties [2]:

1) It regulates room temperature (passive solar design). The high mass of earth material is able to storage a lot of solar warm energy during the daytime, which can be used for heating during the night time.

2) It regulates air-moisture: Human generates moisture (breath, sweating) inside the house. Due the clays moisture balancing and buffering capacity, the natural clays prevent the respiratory system from drying out and prevent or reduce the danger of mould in rooms. Mould is suspected to be one of the most important sources for the growing spread of allergies in industrialized countries.

A European research activity under title Innovative production of high quality indoor earth plaster by adding natural fibre is realizing new industrial processes for manufacturing traditional building materials. Earth plaster re-inforced by cane fibres is a healthy alternative to the use of cement, lime or gypsum based plasters still providing almost the same treatment and strength properties. In comparison to the common earth plasters additives like straw, hemp or lax, certain stellar type of fibres obtained from crops, blossoms and other kind of seed heads bind the soil granulates symmetrically in all directions producing an isotropic strength property.

The problem is now how to arrange the fibre treatment process softly enough to keep the stellar fibre structure undamaged. For this reason the use of a conventional cotton [4] or hemp ginning machine is closed out.

The development process of the fibre handling line has been realized in two steps. The first one includes a set of small-scale laboratory tests of the unit processes as separated and the second one the design and build-up of a pilot plant in a scale, which represents a full production line capable of small production of fibres for earth plasters to be used in limited number of demonstration houses. The experiences of these developments will be utilized later in the design and delivery of a full-scale mass production plant for the fast growing European plaster markets.

One vision is that there is a great market demand as there is a quick growing environmental consciousness and a fast growing demand for healthy and natural building materials. The production can be decentralized and situated at many locations where the proper earth is locally available. The transportation of the cane blossoms over long distances is economically of less relevance, as the material is extremely lightweight.

It is also believed that there is a great market demand and opportunity for the natural earth plaster system, as no satisfactory solution can be found nowadays for the economic production of competitive and high quality earth plasters in Europe. Employment will be created in order to build the new plaster plants, to process the cane fibres and to produce the plaster product. Furthermore, natural earth plaster supports sustainable economic development in remote areas where the needed materials (cane fibre, sand, and clay/loam) will be produced.

2. TASK DESCRIPTION

To get cane fibre production cost lower, defibering process technique must be developed significantly, which means new production machines with higher automation level. The problem is to develop process circuit and related machinery for the complete fibre handling process starting from harvested blossoms and ending to the feed of fibres to the mixing process to make the fibre-reinforced earth plaster.

3. PROCESS DEVELOPEMNT

The complete process consists of the following set of unit process (steps 2…5 in Fig. 1):

1. Harvesting of raw material
2. Quality and quantity control of raw material
3. Storage of raw material
4. Defibering and packing of fibres
5. Storage and transportation of fibres
6. Fibre unpacking and feeding to mixer

The quality and quantity of harvested cane blossom will be analyzed in the cane reception. Collected cane blossoms are packed to storage cases from plastic

sacks and the quality will be checked by visual inspection. Mass of blossoms cases will be weighed and documented with more detailed data (date, supplier, harvesting place, quality).

Storage cases are located and stuck to cane blossom storage complies with "first-in first-out" principle. The moisture content and temperature of air-conditioned storage will be controlled to prevent cane blossom from mushroom growth.

After drying period blossom cases will be carried for defibering and packing unit forward one by one to defibering and packaging line.

Inside the defibering unit, the raw materials will be broken between the rotating brushes (3 units in line), so that blossoms fibres and stems will be separated. Separated fibres and bones will be sucked into a cyclone while the stems and part of separated seeds drops to a collection chamber to the bottom of the cyclone, because of gravity.

Collected seeds and stems can be disseminated back to natural growing area.

From cyclone upper part, separated fibres will be pneumatically transferred to the fibre feeding tower. Final plastic packs filling and dosing will be carried out with soft roll feeding system. Constant filling volume can be achieved with filling tubes. There will be separate tubes to big bags and small bags. After filling tube has a right volume of fibres, the inlet will be closed with thin board of film or carton and the fibres are compressed to a bag with vacuum and pressing equipment. Compressing is necessary to minimize storage and transportation cost. Compressed fibres are also almost hermitical conditions, which prevents mould.

After filling and closing, the bags can be weighed and production information can be added into a possible storage management system. Compressed packs will be stored in temperature and moisture controlled room, where they will be transported to earth plaster production plant.

The control room contains the process control PC and a user interface on the monitor screen. The user interface allows control the rotational speed and direction of variable speed electric motors. The operator has also access to monitor selected process parameters, for example the weight of volume of fibre batches. The interface for rotational speed control is implemented by special software of the motor manufacturer. The other interfaces are implemented with National Instruments LabView graphical development environment software. The data acquisition units are connected to the computer via USB ports

Compressed fibre bags will be emptied to fibre storage box (Fig. 2), which capacity has been dimensioned for *4 hour* continues operation. Fibres will be uncompressed with a fluidising rotor, which will also prevent fibre arching action. From fibre storage box, fibres will be sucked in to fibre feeding tower. Fibres will be fed to the mixer with slow rotating feeding rollers. Upper feed rolls will be dosed right amount of fibre to lower feeding rolls. Fibres dosing will be based on weighing or by adjusting the volume of the lower roll chamber.

During mixer sand and loam filling lower feed rolls will be dosed fibre batch to mixer with constant speed. Fibres will be separated and blown to mixer chamber pneumatically. Fibre feeding sequence will be automated so that the operator will only fill the fibre storage box when it suites to schedule. If sand and clays moisture content is smaller that natural earth moisture content level (*6-10 %*), there will be difficulties to mix fibres uniformly. Mixing generates fibre clumps, which causes to plaster uneven fibre distribution. That could be harmful to end users, because strength properties of ready-made plaster could be reduced.

Problem has been solved by water jet. According detailed laboratory test fibres absorb water to fibre surface. During mixer filling sequence water-jet will be blown inside the mixer to accelerate fibre and clay mixing.

4. DESIGN OF THE PLANT

After specification of the technical requirements of the plant the design task was well defined. After several discussions and testing period some new machinery were developed for the unit processes. Modelling was done with AutoCAD inventor 3D design and modelling software. During design phase the feasibility of the plant design has tested with virtual 3D model by the end users.

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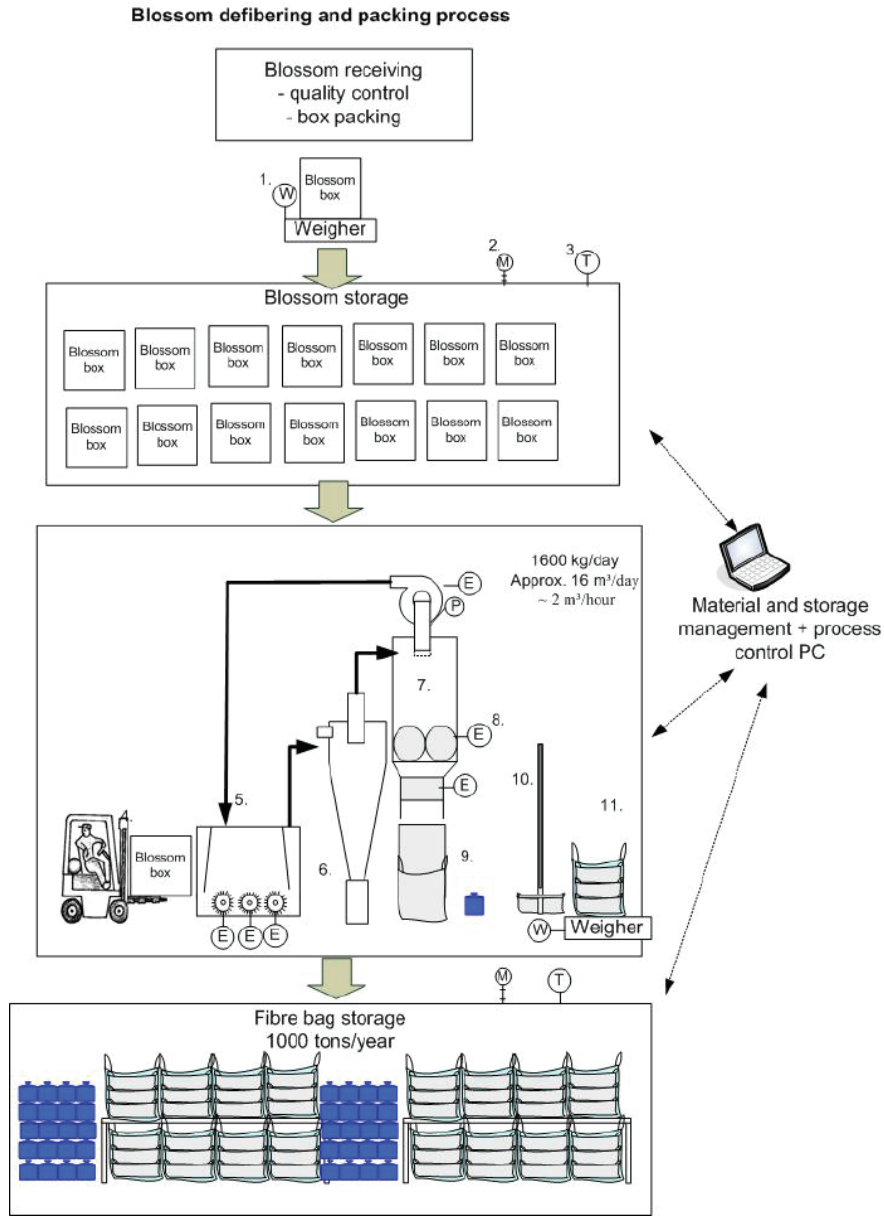


Figure 1 Fibre Production Process

Modular design has been also used to minimize machinery and spare part costs. This principle produced two machines, the defibering-packing unit and the fluidising-dosing unit, which are mainly based on the same principle and on the same design.

The defibering-packing unit (Fig. 2) for the fibre handling plant consists of the following parts for the corresponding unit processes:

1. Defibering chamber for blossoms.
2. Cyclone for seeds and stems separation.
3. Fibre packing tower.
4. Air circulation system.



Figure 2 Fibre Defibering and Packaging Unit

PC based automation system consists of measurements and controls, which are The uncompressing-feeding unit for the plaster plant (Fig. 3) consists of the following parts:

1. Fibre bag handling system.
2. Fibre fluidising chamber.
3. Fibre feeding unit.
4. Circulation air duct and fan system.
5. Water jet unit.



Figure 3 Fibre Fluidising and Feeding Unit

Automation system for Plaster mixing plant is much more demanding than the one for fibre handling plant. The sensing and controlling system for fibres is quite similar but additional constraint is to synchronize the fibre feeding sequence with another one controlling the dosing of soil granulates to the mixer. Materials are transported to mixer with weighing conveyors.

5. CONCLUSIONS

Traditional building materials like clay-based plasters are returning back. Different natural fibres obtained from blossoms of cane plants can be used to produce reinforced earth composites with better strength properties. Industrial production of such materials requires the build of a fibre separation plant and another plant for mixing the fibres with the soil granulates. These plants can stay in different locations or can be combined to one production plant. Both plants utilize a modular fibre manipulation unit, which can be used for defibering and packing purposes in the fibre handling plant or alternatively for fibre fluidising and feeding processes in the plaster mixing plant. The design has been completed by 3D design software AutoCad Inventor. The plant processes are automated by means of controlled weighing, dosing, feeding and conveying operations to produce constant batch size and constant quality mixing results as output of the manufacturing process.

6. ACKNOWLEDGMENTS

The authors wish to thank the European Commission for the financial support to co-operative research project “Plaster+ - Innovative production of earth-plasters”, Contract Number 031287, under which this research has been done.

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VIRTUAL PLANT DESIGN OF INDUSTRIAL MANUFACTURING SYSTEM FOR EARTH PLASTERS

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ABSTRACT

Earth plasters represent traditional building materials, which were earlier used to cover walls of buildings. These materials were replaced about one century ago by lime-cement-sand mixtures. Earth-plasters have introduced again and their excellent properties to regulate indoor humidity have been scientifically explained. The accumulation property of moisture also averages the indoor temperature by means of energy flows during the phase changes, which makes it a very popular solution to be used as indoor plaster in low energy Passive Houses. Earth (loam) plaster is a composite, in which the sand granulate is the filling material, which is glued by clay and bound by natural fibres obtained for instance from hemp. Small amounts of earth-plasters can be produced by manually controlled workshops, but larger production amounts call for a modern automated plant to manufacture the natural plaster-composites like any other industrial end-product in concrete and aggregate business. The design task of such plant by using 3D virtual design tools is described and the results are shown.

KEYWORDS

Virtual Plant Design, Earth Plaster, Traditional Building Materials

1. INTRODUCTION

Traditional building materials [1], which are not based on the use of lime and cement for solidification processes, are typically composed of sand and clay minerals. These pure toxin free natural materials are known to have a positive effect to the indoor climate quality, but they have one weakness, which is the crack formation due to the shrinkage stresses. In order to increase the tensional strength of the composite, a natural fibre component is added. The problem arising now is how to produce such composites in an industrial way so that the fractions of different minerals and fibres are in correct balance [2]. As existing plaster production technologies cannot directly be applied to the production of natural fibre plasters, a co-operation between researchers and plaster producers has been initialised to make a completely new design for a future industrial plant following a “soft production principle”. The developer team consists of designers and specialists in agriculture, soil sciences and building materials [3].

This paper shows the future production processes and the level of automation to be achieved, especially concerning sand and loam treatment from the pit to sales packages. The whole process includes such unit operations as sand and loam mining, sand sieving in pit, biological aging and pre-drying of loam, transportation to the factory, storages, loam drying, loam milling, feeding to the mixing process, mixing, weighing and packaging.

This paper includes process descriptions, 3D models, digital pictures of the production plant and individual machinery with related dimensioning theory. The presentation also highlights the performance of the VR tools (Virtual Reality) [4] in concurrent plant design.

2. TASK DESCRIPTION

A significant difference between the concrete-industry and the manufacturing of earth plasters is the volume of production and, therefore, the size of the production unit. As concrete factories are highly automated [5] with high day-production records, earth-plasters are produced rather manually in plants, where the day-production depends directly on the availability of raw materials and on the current selling demand. Because earth-plasters represent simultaneously traditional materials and green design of buildings, the end-users also expect that the production way is soft in sense that small amount of machinery with low unit power are needed in compact workshops. In fact, the reality that the production plants are owned and driven by SME's arising from the green business sector or by larger farms as a secondary business, corresponds to this figure completely. The increasing growth of the market of low-energy houses, however, calls for larger and larger amounts of natural materials, which need larger production units to fulfil the increasing market demand.

In manufacturing workshops based on manually driven batch processes this leads typically to problems:

1. How to organize the storage and feed of raw materials into mixing units.
2. How to transport materials inside the workshop.
3. How to pack and store the end product before transportation.

In the traditional workshop philosophy one then increases the size of manipulation tools instead of developing the process, which leads to the use of earth-moving machinery in indoor places. As large masses with small payloads are moved back and worth, the energy consumption and therefore also emissions are increasing to such level, which is highly against sustainable manufacturing philosophy.

The purpose is now to show, how a traditional workshop can be reorganized so, that modern production philosophies will not come to conflict with the end-users requirements to make the end-product with a minimum amount of industrial treatment. This work includes the following set of steps in the analysis and design of the plant:

1. Black-box description of the manufacturing process including the flows of raw-materials-in and end-products-out.
2. Design of the process flow diagram including the division of the complete process to a sequence of unit-processes.
3. Development of the unit processes.
4. Development of the materials handling devices to store, dose and convey the plaster components between the unit processes.
5. Lay-out-design of the plant including machinery, storing devices and conveyors following a one-directional propagation of material flow through the plant building.

The object of a case study, where a traditional workshop will be reorganized to a modern production unit, locates in the middle of agricultural environment, where the sources for the necessary plaster components also exist.

3. PROCESS DEVELOPMENT

The complete process consists of the following set of unit processes (Fig. 1):

1. Excavation of the raw materials.
2. Sieving of sand for different fractions.
3. Biological aging of clay and loam
4. Drying and milling of clay and loam
5. Storing to silos.
6. Dosing components from silos to batch feeder.
7. Feeding the batch and fibres to the mixer.
8. Mixing the batch.
9. Conveying the mixing result to packing silo.
10. Packing the plaster granular to sacks.

Manufacturing process of earth-plaster starts in a sand pit where sand is mined with excavators and wheel loaders. This is a natural source of clay, loam and soil, where different soil components are naturally layered as a consequence of geological mineral depositions.

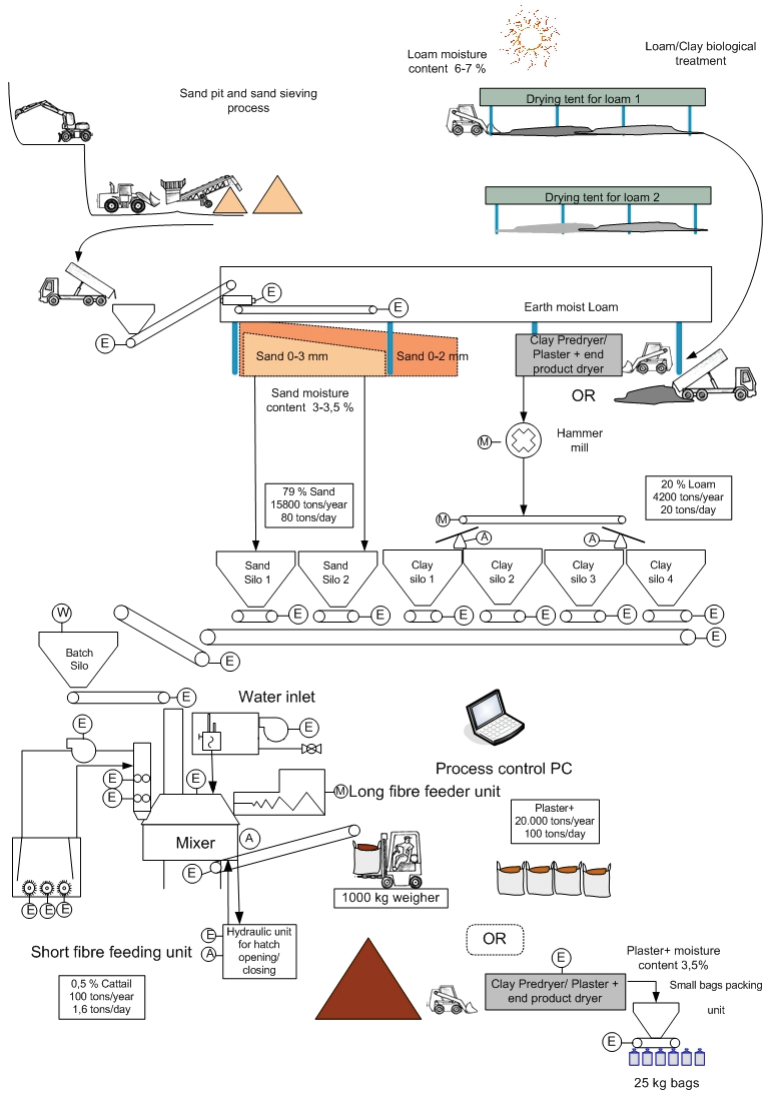


Figure 1 Process Diagram of the Earth-Plaster Production Plant

Sand is sieved to different particle sizes by screening machines already in the pit and transported to a covered storage with a capacity more than *1000* m^3 in *6m* high piles. For further processing the sand is filled to two *30* m^3 silos from which the sand can be fed and adjusted automatically to the mixing process.

Different types of clay and loam are delivered from various mines to an aging process of several months. During aging process the clay is affected by natural micro-organisms, which utilize the organic components of the soil in order to stabilize it in the end usage. After aging the material is dried and milled into finest particle size. Milled clay and loam is stored in four similar feeding silos than the sand.

Granular materials, sand and clay, are fed automatically to the mixing process from totally six similar feeding silos according the recipe of plaster in production. These materials are firstly dosed into a batch feeder and in suitable stage of process the batch feeder is emptied to the mixer.

Also fibres are fed and dosed automatically from filling chamber to the mixer. The moisture of the components is controlled by means of a set of water jets to optimise the adhesion between smaller and larger soil particles.

Mixed plaster is packed to a big bag corresponding to one ton mass of end product and the bags are handled with a fork lift truck.

4. DESIGN OF THE PLANT

After specification of the technical requirements of the plant the design started by measuring and modelling the existing facilities and machinery. After several discussions and a testing period some new unit processes were designed in principle level and the machinery were placed and replaced in an iterative process with the plant owner.

Modelling was done with Autodesk Inventor 3d program [6]. Models were converted with Autodesk 3ds Max to virtual environment [7] and studied in immersed mode by VR4Max visualisation software. With this software the designers and customers are able to study the models from inside as three dimensional visual views. When able to walk around in a virtual factory one can have a better idea of the lay-out and design.

The plant (Fig. 2) consists of the following parts, in which the corresponding unit processes are driven during the manufacturing:

1. Sand and loam storages (Fig. 2, left end).
2. Mixing department (Fig. 3).
3. Fibre feeding unit (Fig. 4).
4. Packing station (Fig. 4).

Sand and clay are stored firstly under roof on floor condition. Before mixing clay is milled by hammer mill and both sand and clay is loaded in feeding silos.

Sand, loam and clay are led to the mixing department by an underground conveyor. Fibres are fed to the process from containers waiting nearby the mixer. Materials are fed and dosed to the process computer controlled according selected program. Filling of the fibre containers and changing of full big bags are made with fork lift truck.

Fibres are sucked and blown pneumatically in closed circuit into a fibre feeding tower. From the tower the fibres are dosed to the mixer by two soft roller nips. Water jet is used to control the moisture content of the granulates during the mixing. This can be regulated to find best performance in mixing. A pan-type mixer developed from a model used in wet concrete mixing is suitable also for this low moisture application.

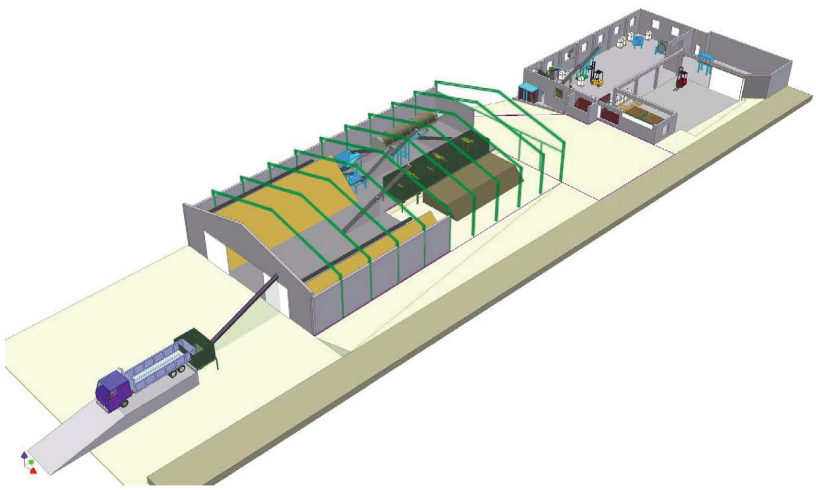


Figure 2 General Overview of Earth-Plaster Production Plant

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Figure 3 Machinery and Equipment of the Mixing Department and Packing Station

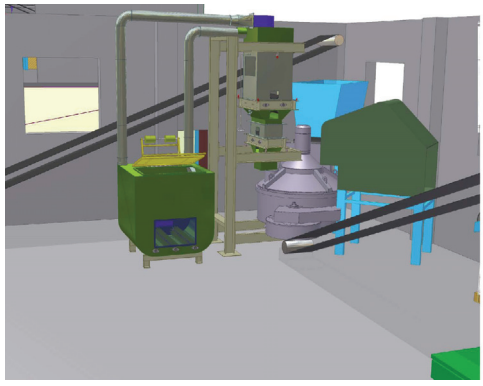


Figure 4 Mixing and Feeding Machinery of Fibres and Soil Granulates

5. CONCLUSIONS

A new factory lay-out was designed with 3d modelling tools. New design improves dramatically the storage capacity of raw materials and the automation level of the process. This design was an interactive process with the plant owners so that several different lay-outs were studied in 3d virtual environment. With visualisation software and special 3d glasses it was possible to show the lay-out design to customers inside the virtual factory. In this way one got better insight to the final plant design and longer development steps could be taken. To complete the plant design, new equipment for automatic fibre feeding were designed and placed to the process.

6. ACKNOWLEDGMENTS

The authors wish to thank the European Commission for the financial support to co-operative research project "Plaster^{+} - Innovative production of earth-plasters", Contract Number 031287, under which this research has been done.

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MASS HOUSING FOR SQUATTER SETTLEMENTS USING PRE-CUT BAMBOO BUILDING SYSTEMS

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ABSTRACT

Aesthetics is not 'something out of this world' that happens in 'Parises' and 'New Yorks' and 'Bombays' and at exorbitant prices." (Vinoo Kaley, cp. "Build your House").

The current work tries to improve, to embellish and to simplify life for slum dwellers by creating a module system for their housing needs. It can be prefabricated, but it can also easily constructed, developed and enlarged by the inhabitants themselves.

1. PROBLEM AND TASKS

The problem of squatters in Bombay is the un-planned manner which destroys future possibilities of development and improvement. It is better to know already different possible last steps when you start with a settlement to keep all opportunities open.

One key to this is urbanism. It is possible to modify afterwards the structure or materials of a single house but it is very difficult to change the urban layout once it is fixed. The houses in this layout should be based on a modular principle so that the settlers can develop their own living space step by step according to their needs and finances.

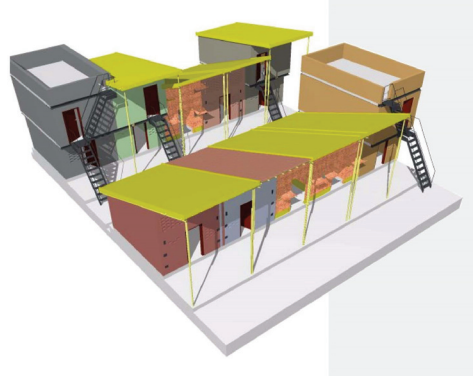
The most expensive good in Bombay is land, followed with distance by materials. Labour however is very cheap. So the first aim is to use the space very economically, secondary the use of material.

2. DEFINITION

In colonies with low rise and high density there are basically row houses with common walls. This is very economically in the use of space and material. The question is how to design these rows.

I want to discuss three possibilities.

In variant A the houses have a path and doors on both sides, but a main orientation to only one side. In type B there is a big way in front of two houses and a smaller one on their back. Variant C has two rows together with three common walls for each house and one big path in the middle.



3. POSITIVE AND NEGATIVE ASPECTS

The airflow is best in A. in type B you require a wind collecting roof which might not work very well and which also costs material and maintenance. In type C there is no airflow. It can be provided only with a fan.

The common space is best in B because you have two rows together which generate an ensemble with their roofs. In C the roofs do not form this unity; in A there is first of all the community of only one row.

On the other hand the problem of B is its back passage will become a very, very dirty area. In these colonies people often do not feel responsible, for consequences the waste and excrements might become the reason for an epidemic disease one day. That is why I discard this solution. In A and C there are no back passages. They have always a main entrance where everyone feels responsible.

If there is a fire you have only one direction to escape in C, in A and B there are two.

Concerning the space requirement C is most economic; A needs larger area for each hut. But if you have two rows on one way the path should be wider (what is often not done). In A you have best opportunities for extension in the first floor in the 3rd or 4th step.

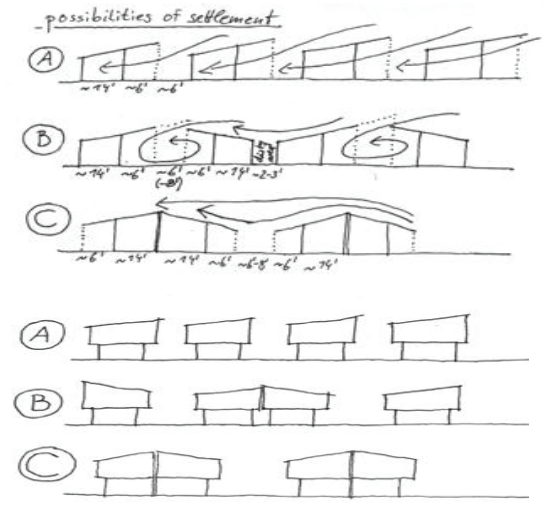
The use of materials is best in C because you can share three walls. In A and B you share only two. But the third side is the smaller one.

All the three solutions can work on a sloping plot.

The possibilities for drainage are very bad in C because you have only one way and it reduces the width of the path very much- especially if it is open in the beginning. In B you can use the back passage but this will become more and dirtier. In A you have best possibilities. You can have one drainage line for each row of houses. They can be constructed easily under ground later.

Overall the best choice is A because it has natural ventilation, precludes dirty areas and has the possibility of extension in the first floor in the 3rd or 4th step. Most common in squatters is C because of its economical use of the plot.

One unit in A requires about 25 sqm (including public way). If you suppose an average density of 5 persons/ hut and 400 plots/ha, you have 2000 people/ha in the first step and 4000 people/ha in the third or fourth when you build the first floor. Of course you require also open public space and places, so there are less than 400 plots on a hectare.

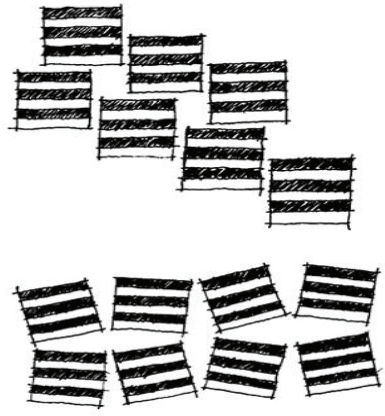


4. ORIENTATION

The orientation should correspond to the main wind direction and to the sun. The wind comes usually from southwest; the sun affects the houses on the roofs and the east and west side. In consequence best orientation means east-west rows with north/south oriented houses. The sun protected main entrance in A is on the south side to allow the wind coming in.

5. URBAN COMPOSITION

One row consists of five to seven houses; three to five rows are one unit; several units compose a colony. The units are very strict and economical in the space use. The public open spaces and facilities are around the units- depending on the needs and possibilities.

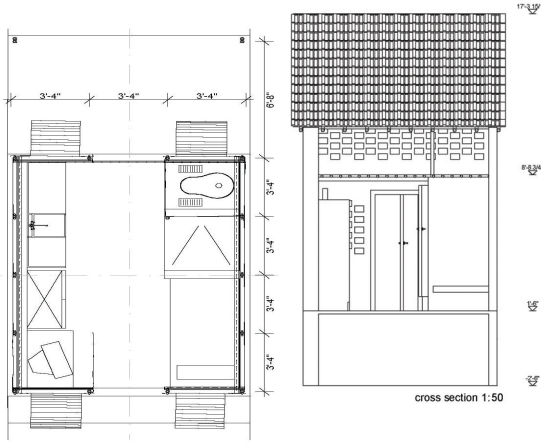


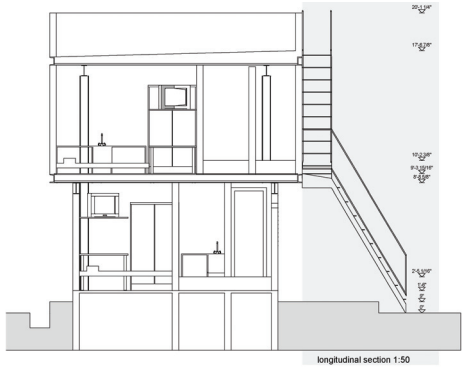
Their layout can be made more interesting by breaking regularity to avoid monotony. Every unit should be connected to a bigger street to give access to the fire brigade and to the police. Furthermore there is parking space required.

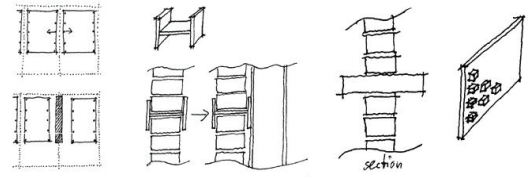
6. DESIGN

A big problem for squatter settlers is the fact that they don't have regular work and income. So there are planned verandas in front of the houses to give them the possibility to produce something and to work at home. These verandas are monsoon protected with a roof. The walls can be replaced by grills to protect property against theft but to allow airflow. If they employed for regular income outside the colony, there can be more people accommodated in this space if necessary. It also can be rented out if there is a big distress. What is more, there should be trees planted on the corners of this space. Inside the hut there is a toilet combined with a shower. It is an Indian WC in the floor where you can put down a wire mesh to stand for a shower. Next to this is a "nahni"- a typical Indian washing opportunity for washing e.g. clothes or dishes, but also for having a shower. It is better to have two separate rooms because you can use both for having a shower if there is a rush. The kitchen should be as far away as possible from the toilet to avoid epidemics.

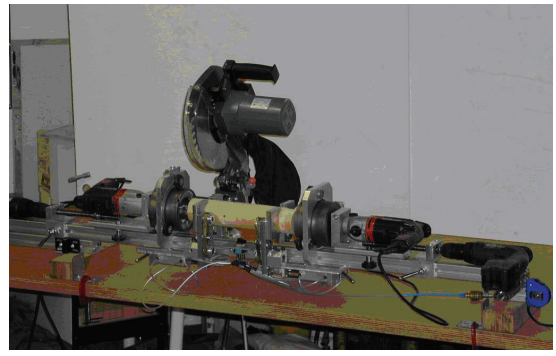
On the back side of the hut there is a small semi-public space of 1'-2' to have a distance between the way and the house and its windows to create a little privacy. There the settlers can make some small-farming or just have a bank to sit down. Below it there can be the drainage.







7. MATERIALS AND SCHEDULE





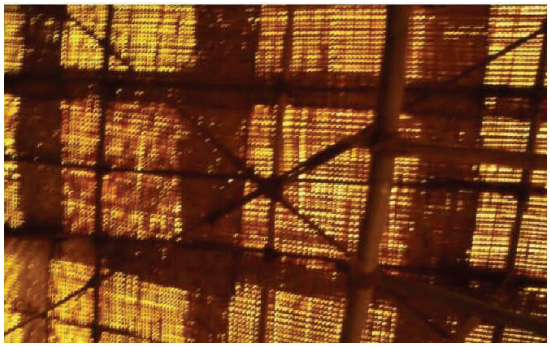


The system is developed modular. The units can be prefabricated; the setting up is done by the inhabitants themselves. For a mass production the nodal points can be improved by standardization and the using of a milling cutter. The mass production will cut costs of the single connection also for low budget requirements. The advantage will be the better quality and security. Renzo Piano experimented also with bamboo connections in

1997 (cp. “Grow your own House”, Vitra Des. Museum).

8. TEMPORARY SHELTER

Sometimes it is sure that you require only a temporary shelter- e.g. for building workers who live on the site during construction or for residents of areas in rehabilitation. In these cases you have a transportable bamboo hut and common toilets and water supply. But anyhow these huts should be organized in the proposed urban layout because it is very common that "temporary" becomes "everlasting". The proposed bamboo hut has a basic module of 3'4" (~1m). A human minimum should be 3 x 6 (= 4+2) m for a family of 5 members- but in reality it is often even less.



Of course other variations are also possible- depending on the plot and the facilities. The materials are bamboo for the structure, chattai (bamboo-mats) for the walls and plastic (light colour) or tiles for the roof. The hut is easily transportable; the users can shift within a day or two. Later, it can be converted into a permanent hut.



9. PERMANENT SETTLEMENTS

If there is a permanent settlement the bamboo hut can be the first step. Under ideal conditions foundation, toilet, water supply and electricity are already given. But in reality there often will be none of it in the beginning. In this case you start with the bamboo hut and variant A if possible. Depending on the political will and the finances the site can get developed. The hut develops from a bamboo structure to a brick house with 1 ½ floors. In this phase the hut has a roof with tiles. Very common are also asbestos cement sheets. They are self-supporting and very cheap but not good for health and climate. Yet there is no iron column or RCC.

But the foundation for a column should already be done for later. We also have to take care of the detailing of the wall. Small "I" section hold fasts are embedded in the wall during construction.

They can be connected later to a column, so that they form together a structure. In the normal building process there is first the column with small "I" hold fasts in the bricks. Here we change the order to keep the opportunity. And this is not much more expensive at this point of time.

In the third step the first floor is built. Iron columns carry the slab of the first floor but the roof is still a cement sheet or better tiles. For protection against corrosion the iron column is inside the hut.





In the fourth step there are also iron columns in the first floor which carry a horizontal cement roof. This is important because the new terrace on the roof is usable space. It can be used as working space but also for sleeping or living. There is also

the place for a water tank. Now the bamboo structure with the roof from the first step can be used again for monsoon protection, shadow and wind collection.

To have a nice character in the settlements they should be painted regularly very colourful- like in the seaface community.

The development is from case to case a bit different. Perhaps there might be one step more or less.

Of course we have to face the problem that most of the existing squatter settlements in Bombay are built in variant C. to allow airflow in these hats you can keep some bricks open and cover them with curtain for view protection. But in this case you have less privacy. Perhaps you can organize it sometimes to shift some of the inhabitants a little to have two smaller families out of a big family together- separated by a door inside the two hats.

10. REALIZATION OF THE HOUSES

In the past there were already lots of programs. Most of them failed. It is important to know how to avoid the same failure.

In the "slum improvement program" (sip) they were given basic amenities like e.g. common toilets, water taps, street lights, open drains and paving of lanes between the hats. *The main drawback was that the land tenure and shelter security was not there.* Why should anybody improve the situation if he/she can be thrown out of area the same day?

Another trial was the "slum upgradation program" (sup). The security of tenure was granted- with a monthly rent. The slum people had to organize themselves in co-operatives. They got the permission of upgrading the condition of their old hats but not of rebuilding it in rcc and bricks. *The problem of this program is the fact that the slum character and the social status of the slum dwellers did not change. Furthermore there was no improvement of the hygienic conditions.*

In the site- and service program (ssp) poor people got a plot for free in an area with proper town planning standards and a credit with a soft loan from the World Bank. There were constructed very simple houses with conventional materials and basic facilities. *But housing is such a big demand in Bombay that the poor sold their houses in underhand deals and returned to the slums. The real profit was made by middleman who exploited the poor and the community.*

The "prime minister grant program" (pmgp) gave a lot of money to improve the infrastructure in slums- especially in Dharavi, the biggest slum of Asia. *But of course this money was exhausted one day.*

The "slum redevelopment and rehabilitation program" (srd&d) proposes to grant higher "floor area ratio" (far) and "floor space index" (fsi). Half of the land is used for rebuilding and rehabilitating squatter people in regular multistoried high-density and high far/fsi-buildings. The other half is exploited for the open market. From this profit the first half is built for free. The aim is to flood the market and bring the real estate prices down. *But often there are created only new, vertical slums. Sometimes the distance between two five-stories-houses is only four meter. For the moment the situation seems to become a little better, but you hardly can improve the situation in a couple of years. You create high-rise high density which creates very often a very high explosive social situation. In Europe these kinds of areas have been build in the sixties and seventies- but with lower density. In some of these areas the situation got so explosive and dangerous that the only way out of this was to blast the houses away and to shift the inhabitants to other areas.*

For the proposed housing system the site- and service program can be a model- with some modifications of course. The settlers should get the plot with a paper for land tenure. This can be a lease for example 30, 50, or 99 years with a monthly rent. This right can be passed on the children or married people but it cannot be sold. But if they are sold the tenure comes to an end and the plot including the house comes back to the city or the state. For assuring this there should be regularly controls.

For the construction of the house there should be a credit with soft interests from the World Bank, the state of Maharashtra or private organizations; the inhabitants can develop their house at once or step by step.

11. NEEDS OF THE WHOLE CITY AND THE COUNTRY

The problem of the slums and squatters in Bombay cannot be solved by this proposed modular housing system. There are further requirements for the whole city and country like to deal with poverty, illiteracy, the growing of the population, the cast system, corruption and pollution. Furthermore the surrounding of Bombay, but also the whole country has to be developed to stop people coming to Bombay. If they have at least equal chances elsewhere they do not come to Bombay.

In the city itself you have to try to pull down the real estate prices. You can make this for instance by building two or three further bridges between Bombay and new Bombay. This can be a very large bridge- a sign for Bombay, a "gateway of India of the 21st century". It should be possible to reach New Bombay in twenty minutes from CST/ VT or Dadar. If the people are faster in New Bombay than for instance in Bandra or Andheri they will shift over there and the prices will adjust on a lower lever over the whole city.

12. FUTURE SCENARIO: INDUSTRIAL PREFABRICATION WITH BAMBOO

Due to the growth of population and to the increasing of human wants the need for raw materials will increase in the presence and in the future. The sources are limited, so the costs jump up. One solution to this problem can be the industrial use of fast growing materials like bamboo. What is more, the local economy will create jobs.

13. ACKNOWLEDGMENT

Thanks to the Director of Rizvi College of Architecture, Mr. Akhtar Chauhan who supported the development of this article.

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LOW COST AUTOMATION USING ELECTRO PNEUMATIC SYSTEM – AN ONLINE CASE STUDY IN MULTISTATION PART TRANSFER, DRILLING AND TAPPING MACHINE

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ABSTRACT

This paper discusses the case study and, comparison of productivity of a component using a real time multi stationed AUTOMATED ROTARY TRANSFER LINE used for Drilling, tapping and inspecting a standard block of size 50 X 50 X 75 mm with drill size diameter 5 x 20 mm long and tapping the drill by M6 machine Tap. The clamping of the component, part transfer and feed of the drilling machine spindle is done using electro-pneumatics. The total logic of the system is based on Low cost automation with the micro controllers. The following studies are carried out 1. Time saved by component handling (loading and unloading), using pneumatic clamping, 2. Increase in productivity both qualitative and quantitative, 3. Improved repeatability and accuracy, 4. Less human intervention, indirectly reduction in operator fatigue, 5. Less rejection due to automatic controls, and 6. Minimization of production costs.

KEYWORDS

Automation, Productivity, Electro-Pneumatics, Micro-Controller, Electromagnetic Relays, Reduction Gears

1. INTRODUCTION

Mechatronics, which is defined as the synergistic integration of mechanical engineering with electronics and intelligent computer control which had propelled fluid power to overcome many challenges posed by other form of energy technologies. The rapid development of electronic interfacing technology had seen the proliferation of electro-hydraulics and electro-pneumatics devices. Fluid, electric and solar powers are some of the energy technologies used for driving modern automated systems. Of these technologies fluid power is mainly reserved for traditional utilization i.e., hydraulic power is normally used in mechanisms and pneumatic power for sequential automation process.

The technology of 'degree of mechanization' is decided upon the principles of minimization of cost, improved productivity both qualitative and quantitative, improved accuracy, better safety etc., which again is posed with higher initial investments, higher maintenance costs etc., Automation is a higher degree mechanization in which human participation is replaced by mechanical, electrical, fluid power technologies capable of doing physical and even mental work as in the case of CNC machines. In some situations automation also demands accurate sensing, recall, memory storage, physical efforts or movements requires special sensors for controlling the technological processes.

2. SETUP DETAILS

A real time multi stationed AUTOMATIC TRANSFER LINE working set up has been fabricated. Drilling, tapping and inspecting on a standard block of size 50 X 50 X 75mm are performed using above set up. The drill size

diameter 5 x 20 mm deep and countersunk is performed then it is tapped by M6 machine Tap.

The set up created consists penta-stationed prismatic body fabricated using L angles 1 ¼" and channels 4"width. The fixed station is welded to the axle and machined for perpendicularity. The bearings are held in a bearing flange, which is centrally fitted to the axle at the bottom of the fixed station through a roller.

The roller connects the rotary table, where 5 stations are arranged. The indexing mechanism is achieved through limit switches for every 72º [1]. The clamping of the component, part transfer, the feed of the drilling machine spindle is done using pneumatics. The total logic of the system is based on Low cost automation with the micro controllers.

One of the main advantages of rotary indexing is that a part once located in the work holder remains clamped in that position until it has passed completely through cycle.

Rotary indexing tables1, the main type of carrier for work that must pass through at least two and up to more than 20 machining operations, reduce the overall feeding functions of the production sequence to the minimum [1]. Clamping and release of the work pieces, is integrated into the work holder, each takes place but once for the complete machining sequence. No orientation of the work is needed between separate stations. Loading and ejection are limited to the first and between first and last indexing stations respectively and the number of workstations in between is immaterial.

Rotary indexing units can be customized in the shop for a specific duty, mostly as a central component of special purpose machine. Drive can be electric, hydraulic, mechanical or pneumatic depending on what power supply is available or what is in the best interests of uniform operations.

The drive for the rotary table motion is through a prime mover – electrical motor 1440rpm. 2-stage worm reducing gear7 set reduces the speed of the motor. In first stage the reduction ratio is 20:1 and in the stage 2 stages the reduction is 70:1. The out put rpm is around 1.3rpm. The output worm wheel is connected by roller, which is firmly held in by two bearings at two ends. The rotary table achieves drive from this roller through fastening. The roller is also held firmly by an axle, which is centrally fastened.

2.1. First Station

Work is loaded in the hopper and ejected by cylinder 1 to the work holder where it is located.

2.2. Second Station

Inspection of overall size of the rectangular block by cylinder 2, fitted with micro switches. If inspection doesn't confirm to standard the job is rejected using cylinder 3.

2.3. Third Station

Clamping of the component in the work holder by cylinder 4, and drilling and countersinking operation by cylinder 5. Feed and retract of the drill is through rack and pinion connected to the piston of the cylinder.

2.4. Fourth Station

Inspection of the drill hole depth by cylinder 6, using micro switches is done. If inspection doesn't confirm to drawing standard the component is rejected by cylinder 7.

2.5. Fifth Station

Work piece clamping by cylinder 8 and tapping of the drilled hole by cylinder 9. Feed and retract of the machine tap is through rack and pinion connected to the piston of the cylinder.

3. SPECIFICATIONS OF MACHINE

3.1. Mechanical

Drilling capacity	12mm
Stroke length	100mm
Spindle speeds	300,700,1000rpm
Tapping capacity	3 to 10mm
Clamping capacity	100mm

3.2. Pneumatic

Cylinder	**Single/Double acting**
DCV	6.35mm
FCV	6.35mm
FRL	12.7mm

3.3. Electrical

Microcontroller	AT89C51
Optoisolator	IC 4N35
Relay Driver	IC ULN 2003
Relay	12V DC, 5A 12V DC, 20A
DCV (solenoid actuated)	DC 24V, AC 230V
Motor	½ hp, 1440rpm ¼ hp, 1440rpm

4. WORKING

The blank is initially stacked in the hopper where the presence is detected by the proximity sensor. The operation starts with the feeding of blank from the hopper to the indexing table and being placed at the fixture by the actuation of cylinder 1. Now the indexing occurs and motor is stopped as soon as the limit switch is actuated at 72°. The length and breadth of the blank is verified using a micro switch setup fixed to the end of cylinder 2. The controller actuates the rejection cylinder depending on the signal from the micro switch.

The blank is again indexed to the next station where the drilling operation is to be performed. First the clamping cylinder clamps the work piece to the fixture. The drilling motor is now turned on and the drill feed is given using a rack and pinion arrangement attached to the cylinder. Now the cylinder is retracted.

In the next station the drill depth is verified by using a set of micro switches attached to the cylinder. The piece is accepted or rejected depending on the signal from the micro switches. Tapping is the operation that is to be performed at the next station. It is same as the drilling station. First the piece is clamped. Then the motor is turned on and tapping feed is given at a very slow speed. A horizontal bar provided between the last and the first station does the unloading of the finished part. The bar slides the work piece out of the fixture.

5. CONTROLLER

The controller used here is a Microcontroller, which has a reprogrammable flash memory. The Microcontroller is provided with built-in ROM which avoids any external memory interface. It has four 8-bit ports. These ports can be programmed both as input or output ports as per the requirement.

In this machine, ports are programmed as two 8-bit input ports and two 8-bit output ports. The inputs include the signals from limit switches, reed switches, micro-switches and proximity sensors. The output signal controls the solenoids and motors through relays and driver circuits. The controller is programmed using assembly language to perform the operations depending on the signals from the switches and sensors. The programming is done in a PC and burned into the ROM using a programmer circuit.

6. ELECTRONIC CIRCUIT

The micro-controller constitutes the brain of the circuit. It generates the required signals for controlling. External circuits are required to drive the relay depending on the signal. The devices used are opto-isolator, relay driver and relays. Opto-isolator isolates the control circuit from the relay circuit. Control circuit is a low power circuit, whereas the relay circuit is a comparatively high power circuit. Any direct connection between these circuits will destroy the control circuit.

The maximum current the opto-isolator can drain is not enough to drive the relay. So an additional relay driver is required. This relay driver can drain the current required to drive the relay. The relays used are 12v DC relays of electro-mechanical type. 5A relays are used for lower loads like solenoids and 20A relays for higher loads like that of motor.

7. ELECTRICAL CIRCUIT

The connections of relays, power supplies and devices like motors and solenoids form the electrical circuit. The circuit includes protection circuits, safety features and provisions for manual controls. Protection circuits includes devices like fuses, circuit breakers, overload protection, over-voltage protection circuits etc., Safety features includes emergency stop button, fault indicators, alarms etc. Provision is also given for manual control of the machine. In case of any malfunctions in the automatic control process, manual control can be adopted. Manual control is also used for maintenance purpose.

8. PNEUMATIC CIRCUIT

The pneumatic circuit comprises of single acting and double acting cylinders, DC valves – single solenoid with spring return, Flow control valves, pressure relief valve, FRL unit and compressors. Double acting cylinders are used for feeding drill bit and tap, where the load is to be handled in the forward and return strokes. Elsewhere single acting cylinders are used.5/2 valves are used for controlling double acting cylinders and 3/2 valves are used for single acting cylinders. Flow control valves4 are used to control the speed of actuation of cylinders responsible for feeding drill bit and tap. Other accessories like pressure relief valves, FRL unit are used for specific purposes.

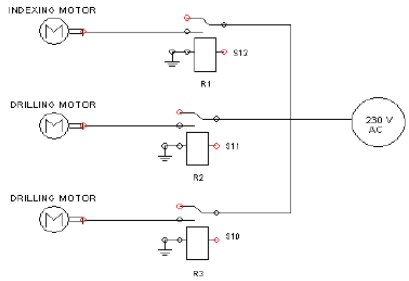


Figure 1 Motor Circuit

9. CASE STUDIES

1. Time saved by component loading and unloading: Initially the time study was conducted by loading the component by conventional means manually. The time taken by the operator was around 10seconds for loading and unloading. For clamping using mechanical vice was around 12 seconds. By using the hopper system wherein components are stacked for every 10 cycles the loading and unloading time has considerably reduced to 3 seconds and also the clamping time of the work piece is only 2 seconds, so a cut down of 17 seconds.(Refer Table 1).

Inspection for quality of the work is traditionally performed after the process. This means that any poorquality product has already been produced by the time it is inspected. Incorporating the inspection into the manufacturing process permits the corrections to the process as product is being made. This reduces scrap and brings overall

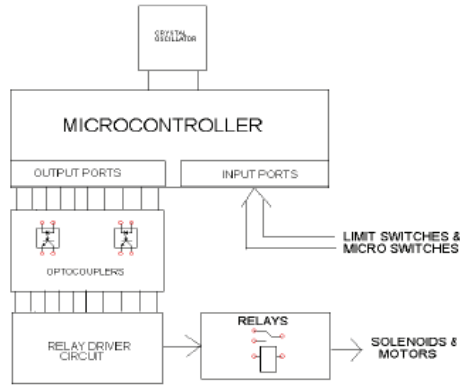


Figure 2 Micro Controller Interface



Figure 3 Photograph of Experimental Setup

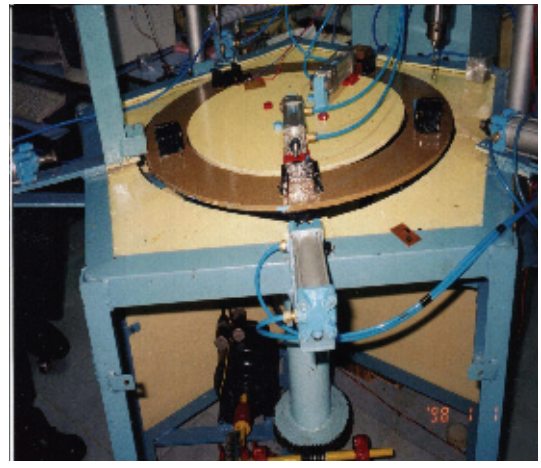


Figure 4 Photo Showing Rotary Indexing Table with Pneumatic Cylinders

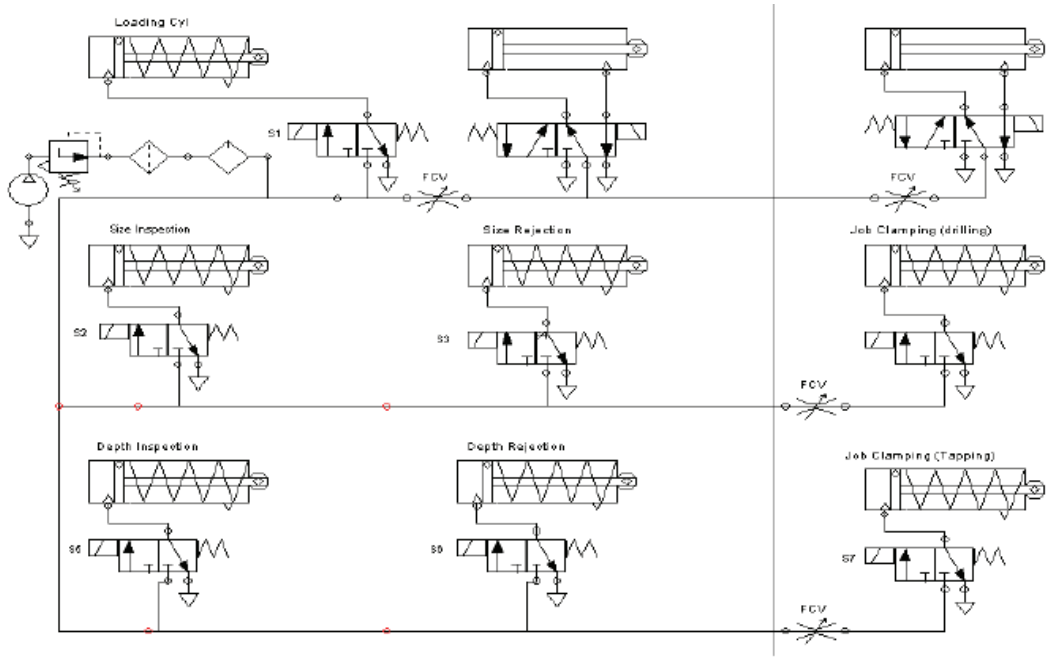


Figure 5 Schematic of Electro Pneumatic Circuit

quality of the job closer to the nominal specifications intended by the designer2 For inspection a separate inspector is required the inspection time is around 3 minutes for each components wherein the component handling, labor cost is again a factor. In the transfer line the inspection is done with the micro switches fitted in the piston end segregates and transfers only the accepted job to the next station. Overall time saved when comparing the standard method of inspection is around 2 minutes and 54 seconds. This process is called On-line inspection.

2. Productivity improvement both qualitative and quantitative 2: Productivity increases by decreasing the lead time of the component, increasing the production rate, reducing WIP.

Manufacturing lead time[2]

$MLT = N_s (T_t + \text{longest } T_o)$

Where, N_s = number of stations,

T_o = operating time.

MLT = 5 (15 + 10)r

= 125 sec = 2 minutes and 5 sec.

Station No	Operation	Setup time (T_o sec)	Operating time (T_o sec)	Non-operating time (T_o sec)
1	Loading	-	3	9
2	Inspection	-	6	6
3	Drilling	2	10	0
4	Inspection	-	6	6
5	Tapping	2	10	0

3. Improved repeatability and accuracy: Half degree accuracy is achieved in indexing the table through the limit switches beneath the fixed table. Repeatability of 0.95 is achieved for indexing operation and the central axis of the job in drilling and tapping operation.

4. Less human intervention: Drastic reduction in the work load is attained through the automation process which directly helps in less operator fatigue. This reduces the labour cost.

5. Less rejection due to automatic controls: Because of high accuracy and repeatability achieved due to automatic control system, rejection of components is reduced.

6. Minimization of production costs: Increased production rate, reduced production costs, reduced labour costs, reduced WIP, minimises the production costs.

10. CONCLUSION

The concept of automated part transfer line fabricated as an experimental setup can be extended to an industrial application with further modification in the manufacturing and assembly process to achieve quality in the machine as per the test charts provided by leading machine tool manufacturer. On a whole, it is concluded that the automation is an inevitable process though the rate at which it should be introduced will have to be carefully planned in order to bring social justice and to accrue economic benefits.

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AUTOMATIC WAFFLE SLAB TECHNIQUE FOR HIGH-TECH FACTORY

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ABSTRACT

Under the continuous compression of life cycles for products from the high-tech industry, all investors expect to recoup an enormous amount of investment within the shortest possible timeframe and raise production rapidly, so they can acquire more market opportunities and improve market share. In view of this, investors desire to shorten plant construction as much as possible.

The return air floor slab for the clean room is one of the key construction projects. This floor is a common design used in high-tech plants to control the cleanliness and humidity of the air. Concentrated openings and large thickness are the two major requirements for it. Under these two requirements, levelness and resistance to minor vibration of the floor slab must also be considered; this has caused significant difficulties in construction, where many vendors are also confronted with pressures for construction time and quality.

In order to solve the difficulties in waffle slab construction, this study has proposed a technique of precast waffle slab to meets the requirements for the high-tech industry on construction time and quality under intense market competition.

KEYWORDS

High-Tech, Precast, Waffle slab

1. INTRODUCTION

In recent years, the high-tech industry has taken on an important role for the economic development of Taiwan. From the design and manufacturing of semi-conductor chips to TFT-LCD, the size and complexity of plants have increased continuously. Current limits for land and production paths mean that the plane dimensions for plants are frequently limited to 200m*300m, thus the design of multi-floor plants are an alternative for greater efficiency. The multi-floor plant is defined as a plant design with a production line in a vertical format and such design can enhance the efficiency of land use substantially. Since the vertical format of the plant functions motivates closer relationships between product quality and structures, many special requirements for plant construction have been derived and constitute challenges to construction technology.

The air return floor slab is a common design used in high-tech plants for controlling air cleanliness and humidity. Concentrated openings and great thickness are the two major requirements for floor slabs for the abovementioned plants. In the high-tech industry with intensive market competition,

time happens to be one of the key elements relating to product success, where many vendors have also confronted distinct pressures for shortening construction time. The quality, construction time and cost are often the demands from a client on construction works, but these three demands often influence different results under for the difficult and complex work.

The traditional technique for high-tech plant construction face many problems during construction and the precast floor slab is one of the most effective solutions; this study will compare the differences between the two methods practically, and follows by analyzing the production and work with the precast system further.

2. PROBLEM STATEMENT

Products in the high-tech industry change at a rapid rate and with a continuous compression of life cycles. Investors wish to recoup an enormous amount of investment within the shortest possible time and raise production rapidly, so they can acquire greater market opportunities and improve their market share. In view of this, the construction of a high-tech plant must comply with the characteristics of the industry. For construction of such a high-tech plant, the quality of the return air floor slab in the clean room is very important since such slab is constructed in a large area; as for the most important requirements on waffle slabs, namely the "resistance to minor vibration" and "levelness of the floor slab", traditional construction often faces challenges on quality and construction time and the main problems are as follows:

- The work quality and precision are not easy to control
- Labor safety
- It is difficult to shorten construction time

In order to solve the above-mentioned problems generated from traditional construction, this study proposes to apply a thorough precast technique from preliminary planning to production of precast components.

3. CONSTRUCTION TECHNIQUE FOR WAFFLE SLAB

3.1. Traditional Technique

Since high-tech plants occupy a very large area, each floor has a large span and the length/width of the waffle slab may reach 100 m. In the traditional technique, the materials are stored onsite first and supports are established for worker convenience. After completion of the supports and formwork assembly, workers can start cutting and tying the reinforcement, which is followed by inserting the opening steel cylinder into the reinforcement and the structure is ready for grouting. After curing, the formwork is removed and the waffle slab is completed.

However, traditional construction of waffle slabs will cause an excessive waste of manpower, machinery and materials, in addition to various wastes that occur at each construction step, there are still many problems such as occupancy of site space, disordered environment, mold damage, theft risk, labour safety problem, formwork deformation, high dependence on skilled labourers and long time for waiting the EPOXY evaporation of moisture in the concrete which need to be improved for the cast-in-place technique.



Figure 1 Traditional Technique Problems

3.2. Precast Technique

Before production of the precast waffle slab at the precast plant, material must be planned first, where the production components are then modulated. After that, the precast components are produced in the plant and the finished products are delivered onsite after completion. Hoist machinery is used to hoist the waffle slabs to the construction floor for assembly. Altitude positioning is then carried out after hoisting, which is followed by concrete pouring for connection.

The each step solves the problems in traditional technique as follow:

- Precise construction and modulation: It solves the site space occupied by materials, disordered site environment, damaged steel cylinders, risk of material theft, waste from material consumption and repetitive works
- Production of precast components: It solves the obstruction of construction path, labor safety, deformation of formwork, high dependence on skilled laborers, height difference generated from steel cylinder, displacement or deformation of steel cylinder, interior contamination of steel cylinder, displacement or deformation of steel cylinder and adverse workability.
- Hoisting of machinery: It solves the bursting formwork and supports during grouting, curing period for concrete is too long and failure of compressing construction time for work on single floor.
- Altitude positioning: It solves the uneven floor surface.
- Pouring concrete for connection: It solves the construction area is too large and cannot be completed at once.

For precast technique, since the slab units are produced in advance, the precision and levelness are easier to control during production. With the measurement of altitude positioning during onsite assembly, the altitude difference between the slabs can be reduced to ensure compliance with the design requirements. In addition, the strength of the precast slabs are sufficient to sustain their self weight and work load, thus no work platform or supports need to be set up, which improves the construction path effectively. Finally, since the precast technique removes traditional site operation with more difficulty away from the critical path, the site is only left with hoists; thus multiple floors can be constructed at the same time and the construction time can be reduced effectively.

4. PRODUCTION OF PRECAST WAFFLE SLAB

4.1. Planning Production Procedures for Precast Waffle Slab

In order to prevent waste from traditional construction and the abovementioned problems, the path of material use and supply must be planned before manufacturing the precast waffle slabs. Moreover, modulated production of waffle slabs shall be considered to comply with the limits of the load bearing hoist machinery, which reduces unnecessary waste, as well as increasing construction efficiency and benefits.

For material use planning, problems such as material waste, secondary fabrication onsite and failure of timely material supply occur most easily with traditional cast-in-place construction. In the process of traditional cast-in-place construction, obstruction of the construction path is the greatest problem because the traditional cast-in-place construction requires enormous amount of supports and formworks. This causes limitations to the construction paths of personnel, machinery and material.

In order to prevent these problems during the production of precast waffle slabs, the following principles can be applied:

- Make the size of the material consistent with the specification on the design drawing upon entry to the plant to reduce resources and manpower wasted during production of reinforcement, as well as secondary fabrication or cutting.
- Order materials in batches according to the amount of work sequence planned. Such amount must not be excessive or ordered all at once, otherwise, the work space will be occupied for a long term, which affects the construction path and increases expenses for material arrangement.
- The entry of material shall not be too early or late, and must be delivered on time according to the site regulations
- The material (components) piled within the fixed storage area shall comply with the operation sequence of the site operation,

where storage is executed with coding at fixed space for ease of searching.

- Deliver the material to the assigned area for storage and fabrication with transportation resources planned in advance.
- During production, plan the material delivery, quantity, application time and application method for construction tools.
- The construction site is planned with a fixed path for material delivery (including horizontal delivery and vertical hoisting).

4.2. Production Procedures for Reinforcement Cage

Before production of precast waffle slab, the reinforcement cage must be planned and produced first. The procedures are as follows:

- Planning for the reinforcement material
- Fabrication of reinforcement and hoops
- Reinforcement assembly and placement in x and y axis.
- Tying reinforcement cage.
- Assembly completed.



Figure 2 Reinforcement assembly and placement in x and y axis.

4.3. Production Procedures for Precast Waffle Slab

This study has proposed two types of production for precast waffle slab, namely the semi-precast waffle slab and fully-precast waffle slab. Since each floor of a high-tech plant has different requirements on loading capacity, such capacity shall be designed according to the layout of the facilities on each floor. Floors with greater load capacities shall use thicker floor slabs. However, there is a load limitation for precast floor slab when hoisted with machinery, thus thicker slabs will not be able to be hoisted with machinery. In view of this, the study has proposed the semi-precast waffle slab for floors with heavier loading and greater design thickness, whilst fully-precast waffle slabs are adopted for floors with lighter loading and thinner design thickness.

In a high-tech plant, if the floor load is great and a thicker floor slab must be used, a fully precast slab might be too heavy for the machine to hoist under consideration of the loading limitation of the machine, thus the construction of a semi-precast waffle slab is adopted. The construction principle is to adjust the levelness and dimensions of the steel mold for the precast waffle slab first, which is followed by cleaning, placing a base cover over the opening of the mold, hoisting the reinforcement cage, placing the opening mold, pouring and curing the concrete to complete the semi-waffle slab, where the slab is hoisted to the construction floor for completion of pouring.

If the floor loading is not large, a floor slab with a smaller designed thickness can be adopted. During precast production, since the floor slab is thinner and lighter, a fully precast technique can be adopted within the load limitation of the hoisting machine. The construction principle is to adjust levelness and dimension of the steel molds for precast waffle slabs first, which is followed by placing the steel cylinder base cover, hoisting the reinforcement cage, placing the steel cylinder, pouring and curing the concrete, and then coating EPOXY on the surface for completion.

4.4. Hoist the Precast Waffle Slab

During construction of a high-tech plant, steel girders can be installed on the columns after completion of the foundation and column erection. For precast columns between the 1st and 2nd floor, the space between the columns allows entry of a wheel crane, thus slabs can be hoisted with wheel crane accordingly. For floors above the 2nd floor, wheel cranes cannot be used since the girders will obstruct the boom extension. In view of this,

waffle slabs above the 2nd floor will be installed with a overhead crane. In traditional construction, the floor slabs only allow construction on a single floor; with a precast hoist however, the wheel crane and overhead crane can work at the same time, thus simultaneous slab installation can be executed on each floor. In this way, construction time compression problems stemming from construction on only single floor with traditional construction can be improved upon significantly.



Figure 3 Precast Waffle Slab Production



Figure 4 Hoisting the Precast Waffle Slab

5. BENEFIT EVALUATION

When waffle slabs are made using the precast technique, they can be divided into fully precast and semi-precast slabs. The following content provides a comparison between the precast technique and the traditional cast-in-place construction:

- Construction time: From the table below, it can be seen that the fully precast waffle slab onsite is only left with hoisting operations and it can be executed on multiple floors simultaneously; this provides the fastest construction speed of 1.5 span/day. For semi-precast waffle slab, since concrete pouring and curing are still required onsite, the construction speed can only achieve 1 span/day. For traditional construction, since all operation is carried out onsite, the construction speed is the slowest at only 0.5 span/day. Therefore, the precast technique does provide a significant effect on the compression of construction time.
- Safety cost: Since the waffle slab with precast technique is produced in precast plant almost completely, the site is only left with hoisting operations, thus massive scaffolds and formwork supports can be reduced. Moreover, the chances of elevated work and debris generated from construction are also reduced. Since the site does not require storage for large amount of materials, it provides great assistance to maintaining the environment. Therefore, the security cost of the precast technique is only 1/5 of the traditional technique.
- Manpower demand: From production of the reinforcement cage to precasting the waffle slab, the precast technique mostly uses molds to assist in production. Since the materials used are well planned, the hoisting operation onsite only requires machinery and a few skilled laborers to complete the work. Taking a fully precast waffle slab as example, the work takes only 17 workers/day; the semi-precast needs 30 workers/day since concrete pouring is still required onsite, whilst the traditional cast-in-place technique requires the largest number of skilled laborers at 105 workers/day, because all operations are completed onsite. Given the deficiency of skilled laborers nowadays, the precast

technique helps solve this problem efficiently.

- Reinforcement consumption: Since the precast technique for manufacturing reinforcement cages is planned for the reinforcement use in advance, the materials are consistent with the dimensions specified on the design drawings upon entry to the plant, which reduces resource wasted from secondary fabrication or cutting during production of reinforcement. Compared to traditional cast-in-place technique, the precast technique provides a lower consumption of reinforcement.
- Unit rate: Since the fully precast technique is only left with hoisting operations onsite, its unit rate can achieve 9(slabs/day)*30(M2/slab). The semi-precast method still requires concrete pouring and curing onsite, thus the unit rate is lower than the fully precast technique, but can still achieve 6(slabs/day)*30(M2/slab). For the traditional cast-in-place technique, since all operations are executed onsite, the unit rate is relatively lower and only achieves 3(slabs/day)*30(M2/slab).
- Workability: The precast technique and the traditional technique each has its own advantages and disadvantages. The precast technique improves problems faced under traditional technique significantly, but requires a longer time for preliminary planning; if design variation occurs, tremendous influences will be caused to the precast production. Although there are still many construction problems worth discussing for the traditional technique, it required a shorter time for preliminary planning and is therefore more flexible against variation.

6. CONCLUSIONS

Facing demands of construction speed for high-tech plants, this study proposes the precast waffle slab technique to reduce unnecessary waste during production, so modulated operation can standardize the basic conditions of products during production, which provides stable and consistent quality. The operations of reinforcement cage prefabrication and precast waffle slabs not only reduces site works, but also implements critical operations in advance and speeds up the work progress. To improve the hoisting methods, different hoist machines are used to simultaneously hoist fully and semi-precast waffle slab, which further accelerates the construction progress. With variation in automated production and hoisting methods, the precast waffle slabs are not only capable of improving upon the inconveniences of traditional construction significantly, but also achieve the requirements of a shorter construction schedule for high-tech plants.

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