An Innovative Construction Process-Contour Crafting (CC)

Dooil Hwang and Behrokh Khoshnevis

***Abstract*— This paper describes an innovative construction automation approach using a new Layered Manufacturing (LM) process called Contour Crafting (CC), which has been developed at the University of Southern California. In the CC construction process, a precise amount of mortar mixture is delivered to make a concrete mold using robotic techniques. Mortar mixture is added in a layer by layer fashion; then a volume of commercially available concrete is poured with a certain time delay between batches. The CC construction process has great potential in construction automation due to its relative simplicity, low cost, and capability of being easily integrated with currently available automation technologies. This is demonstrated by CC's unique capabilities and experimental results in fabricating a full-scale concrete wall structure using ordinary construction materials.**

***Index Terms*—Contour Crafting, construction automation, fabrication, rapid prototyping, layered fabrication process.**

I. Introduction

Current "cast-in-place" construction process has been used in the field since Roman ages. The Romans revolutionized many construction techniques including concrete form design and methods to construct arched and domes. The process most likely developed by the Romans is still employed in the modern construction field which requires high intense skilled labor forces in order to do construction practices.

Our modern living standards have been tremendously changed due to the industrial revolution. Today robotic systems routinely replace many complicated, tedious, and dangerous human production activities in a variety of manufacturing applications. For instance, the price and quality of goods and services have been dramatically reduced and improved by utilizing modernized science and engineering knowledge except construction industry [1].

Current construction industry still remains labor intense and craft oriented industry which causes several serious problems in the areas of productivity, quality, safety, and skilled labor shortages. In order to address these issues, various types of automation and robotics technologies have been proposed and implemented [2]. These attempts however have not returned significant improvements and little has been contributed to solving the problem. A major obstacle has been that the construction industry is steeped in high skill, labor intensive conventional processes, not conducive to adaptation of automation technologies.

To be successful, construction automation will require a paradigm shift in process technology. Here new novel construction process technology, Contour Crafting (CC) construction process, fits in this category and has the potential to revolutionize the industry, changing it from the conventional "cast-in-place" paradigm to a layer by layer approach.

II. THE CURRENT STATE OF AUTOMATION IN CONSTRUCTION SITES

During the last 18 years, construction automation and robotics have been implemented at various extents to address problems facing the construction industry such as productivity, quality, safety, high costs and skilled labor shortages in the United State and Japan [3]. The Japanese construction industry, in particular, is very active in automated construction research, seeking a solution to the skilled labor shortage. Many large Japanese construction companies have their own research centers with sophisticated equipment and large staffs researching new construction technologies.

There are two categories of automation considered by construction companies. The first is using single task robots that can replace simple labor activities at the construction sites. Single task robots can be classified by four different types-concrete floor finishing, spray painting, tile inspection, and material handing. Approximately 89 single task construction robots have been prototyped and deployed in construction sites in Japan [4]. The introduction of robotics directly at construction sites has contributed to productivity, safety, and quality improvements. Yet, the contribution of robotics at current levels is not revolutionary and current automation approaches are still geared toward conventional processes. Automating conventional processes is invariably expensive; so, the cost savings is minimal. Fast changing construction processes and project complexities create complicated requirements and exceptional challenges for automation

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technology to adapt.

III. Expensive automation technology adaptation in construction sites

Using conventional automation technology, implementing a fully developed automated system that will address the problems facing the construction industry will be expensive.

A. *Complicated formwork practices*

In currently prevailing concrete construction, formwork is an important practice since any formwork problem leads to poor concrete quality. Poor quality in turn can cause serious accidents, death, and property damage.

Figure 1 shows a schematic of a typical wall formwork, including steel reinforcements. In traditional construction, components such as sheathing, ties, wales, studs, and braces are assembled manually by workers according to design. Formwork must be designed and erected such that it is capable of supporting about 150 pound per cubic foot of fresh concrete. The form must withstand all vertical and lateral loads including loads from equipment, workers, various impacts, and strong wind.

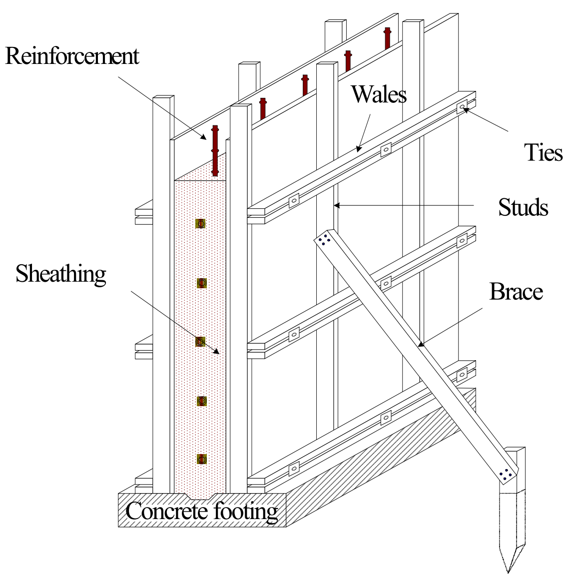


Fig.1 Basic components of a typical wall formwork

B. *Complicated reinforcement installation*

Installation of reinforcements is another labor intensive practice. Since concrete is weak under tensile and bending loads, embedding reinforcements are crucial for structural concrete uses. Steel reinforcements should be placed at the weakest positions in the concrete mass, most vulnerable to bending / tensile loads. Figure 2 shows an example of how complex reinforcement installations could be. Adapting existing automation and robotics methods to perform these tasks would be incredibly challenging.

These two labor intensive construction processes, formwork and reinforcement, must be automated efficiently for any promise of economic return. The sheer complexity explains why the previous 18 years of construction automation development (mostly by Japanese companies) have resulted in insignificant advances, practically speaking.

Fig. 2 Complicated construction practice hard to be automated [source: DER SPIEGEL, in German, 8, 2004]

The problem we face is not merely a matter of complex design, wide range of materials, or construction conditions. Conventional construction processes “cast in place” should be replaced with a new innovative process. A new paradigm is needed which seeks to increase or at least maintain the same degree of quality and effectiveness as conventional construction process. The new process technology should be able to integrate with current automation and robotics technology without paying too high of a cost.

IV. The needs for an innovative construction process

Previous attempts at automation by the construction industry have resulted in insignificant returns in productivity, safety, quality. The current state of automation and robotics technology is not sufficient to economically replace skilled labor. The construction industry needs to think “out of the box” and seek alternatives to existing fabrication and assembly process. The new approach must consider adaptability to existing automated construction technologies and processes.

In recent years the Rapid Prototyping (RP) process has been implemented in a variety of applications and disciplines such as architecture, automobile design, aerospace and medical industries. Rapid prototyping (RP) is a material additive manufacturing process by which objects are created by computer controlled, layer by layer sequential material deposition. By using Computer Aided Design (CAD) packages, a 3D solid model of a part is decomposed into numerous cross-sectional layers. The cross-sectional geometries are mapped to material layer deposition paths, and fed to the RP machine where the physical 3D solid model is created in a layer by layer fashion. RP processes have significantly reduced the high cost and cycle-time of new product design and manufacturing. One goal of using the RP process is to verify the form and fit of new design concepts early in the product development stage, prior to final production. There are several

commercialized RP systems that make high fidelity prototypes with precise dimensional accuracy and surface finish.
The main merit of the RP is the capability of fabricating complex structures, as shown in Figure 3. However, RP systems today are not suitable for fabrication of larger scale parts except Contour Crafting (CC) - a special RP technology developed at the University of Southern California (USC) [5].

Fig. 3 A complex geometry (Hagia Sophia in Istanbul) fabricated by a RP process [Source: MIT 3DP Laboratory]

CC technology adapts RP capabilities and extends them to the field of large scale construction. As in other RP methods, in Contour Crafting (CC) material is added layer by layer according to a computer controlled sequence.

V. THE CONTOUR CRAFTING PROCESS

This newly patented CC process technology is suitable for rapid fabrication of large-scale complex shaped objects with smooth surface finish. The CC process is based on an extrusion and filling process illustrated in Figure 4. The extrusion process forms the smooth object surface by constraining the extruded flow in the vertical and horizontal directions using trowels. A schematic view of extrusion using two trowels is shown in Figure 5.a. The orientation of the side-trowel is dynamically changed for better surface fit for each decomposed layer.

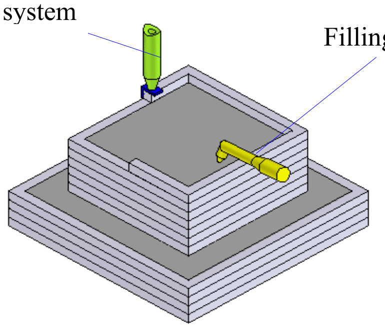
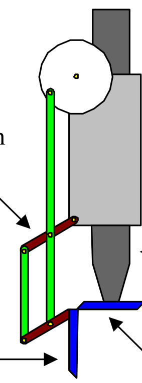


Fig. 4 Extrusion and filling mechanism

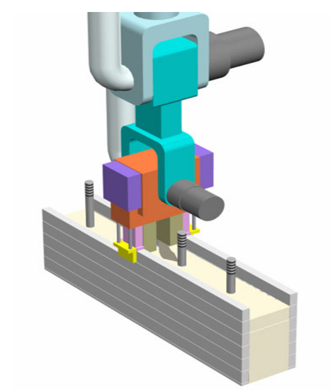
The side-trowel allows thicker material deposition while maintaining high surface finish. Thicker material deposition cuts down manufacturing time, which is essential for building large-scale parts using the additive process. Maximum deposition layer thickness is limited by the trowel height.

As the extrusion nozzle moves according to the predefined material deposition path of each layer, the rims (smooth outer and top surface of outside edges) are first created. The troweled outer surface of each layer determines the surface finish quality of the object. The smooth top surface of each layer is also important for building a strong bond with the next layer above. Once the boundaries of each layer are created, the filling process begins and material is poured or injected to fill the internal volume.

At the bottom of Figure 5 a compound nozzle assembly is shown by which concurrent extrusion of two wall sides and filling of the previously built layer may be performed.



(a)



(b)

Fig. 5 CC single nozzle (a) and multiple nozzle assemblies (b)

VI. CURRENT STATE OF CC RESEARCH AND DEVELOPMENT

Contour Crafting has been the focus of intensive research at the USC rapid prototyping laboratory. The laboratory has been improving CC's superior surface forming capability, speed, part size and nozzle designs [6-9]. Various research materials have been tested and evaluated to date. Rapid advances in this research will be a critical if CC is to be considered as a viable option for construction automation.

A. CC Machine Design

A simplified and specialized CC nozzle system with three axis motion control was developed for constructing the full scale wall demonstrator. The new CC system, shown in Figure 6, consists of an extrusion system that conveys a mortar mixture from the material reservoir and deposits it in controllable amounts to form the desired shape. A piston is attached to and driven by the lead screw which turns at constant rotational speed to extrude the mixture. As the mortar exits the extrusion nozzle, the machine moves the nozzle assembly in the X-direction at a specified speed.

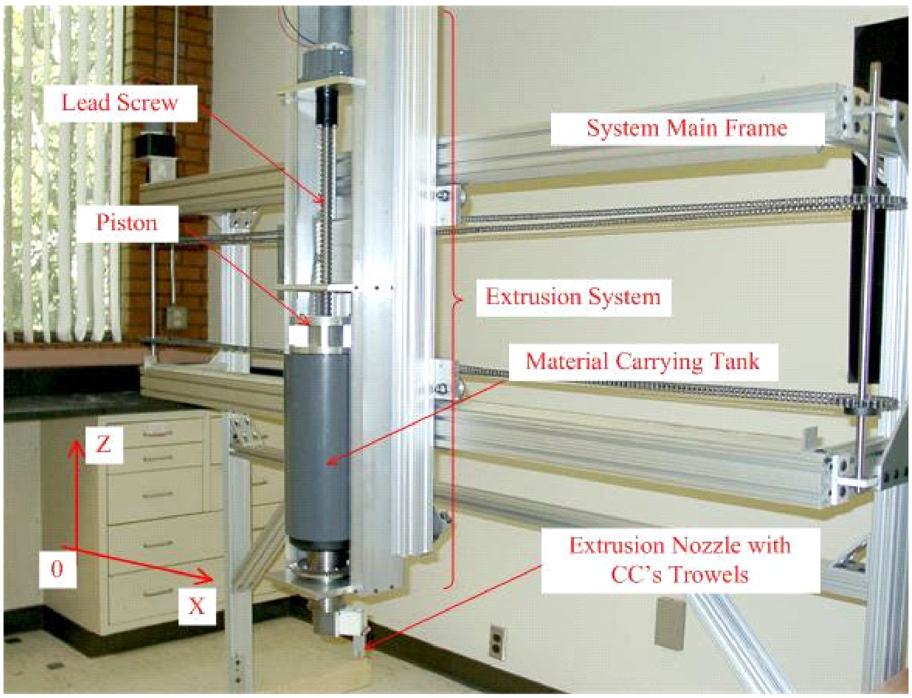


Fig. 6 A new CC machine for fabricating a concrete wall

Once the system completes one layer cycle, the entire extrusion assembly moves vertically an incremental distance equal to the height of the next layer. The cycle is repeated until the final shape of the boundary is established.

The main structure supports and precisely guides the entire extrusion system during fabrication. The machine frame has two rails with V-shape profiles that guide the extrusion system. The current system permits extrusion only in the X and Z directions, therefore limited in the types of 3-D objects that can be created.

B. Mortar mixture development and its compressive strength

Extruding a dense mortar mixture through a small nozzle orifice is quite difficult. The optimum mixture ratio of cement, sand, and water necessary to fabricate a concrete form depends on the application. Through several trial and error experiments, a mixture characteristic found to be suitable for the new CC machine is as follows;

- Type II hydraulic Plastic Portland cement: 9.5 lb
- Sand: 10.5 lb
- Plasticizer: 0.8 lb
- Water:4.8lb

To verify its early compressive strength, three cylindrical test specimens, 5 cm X 10 cm (2” X 4”) were made and cured for 7 days in room temperature.

Tests were conducted at USC’s Civil Engineering structural testing laboratory with the results shown in Table 1.

The results indicated that the compressive strength of three test specimens were both consistent and adequate for their use as a permanent structural component of the finished concrete wall. Our research team in collaboration with industry is aiming at the use of mixes that can cure to near maximum strength in a few hours.

TABLE I
RESULTS OF TESTING COMPRESSIVE STRENGTH

Cylinders	Compressive strength (PSI)
Specimen 1	2,786
Specimen 2	2,830
Specimen 3	2,606
Mean	2,741

C. Fabrication

The mortar mixture was prepared using power drill driven mixing paddles and was loaded into the material carrying tank, shown in Figure 8. The velocity of the extrusion system in the horizontal direction was set to 20 mm/sec with stabilized continuous extrusion flow from the CC nozzle assembly. Initial extrusion flow is discarded until the flow is stabilized and the system starts its fabrication.

Once an entire batch of the mortar mixture loaded inside the material carrying tank is used up, the CC system pauses until another batch of mortar is loaded and the extrusion continues to form the remaining concrete form. A batch of mortar is consumed in approximately 10 minutes and yields a concrete form approximately 64 mm (2.5") high. To complete the intended geometry, nine batches were needed. The final concrete form fabricated by the CC system exceeded a height of 60 cm (2 feet) and is shown in Figure 7.

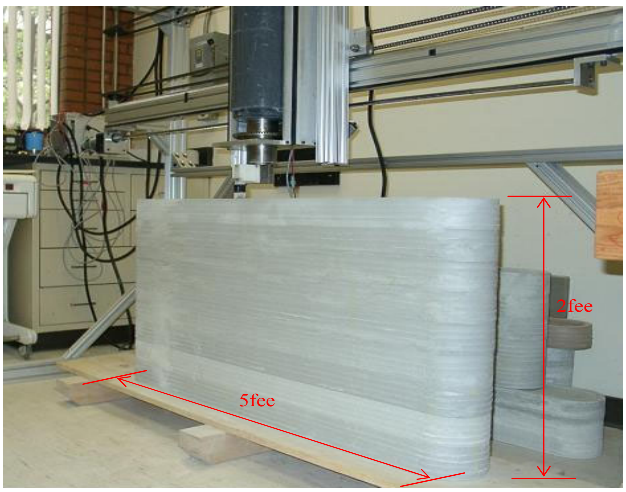


Fig. 7 A concrete form of desired span and height fabricated by the CC machine.

D. *Lateral pressure against concrete mold*

For CC applications, pour rates less than 13 cm/hour (5"/hour) will allow erection of a 3 meter (10 feet) tall concrete wall without using special high strength form materials. Once concrete inside the form hardens, pressure is no longer generated below the level of fresh concrete. It is not necessary, however, to wait until the concrete hardens completely since even partially cured concrete generates minimal lateral pressure on the form. Figure 8 illustrates the CC concrete pouring process.

The bottom cross-hatched section represents concrete which has been cured for one hour. The cured concrete produces minimal lateral pressure on the form but the exact value was difficult to quantify in our experiments. Data was not available in the available literature; therefore, a simple test was devised to validate the strength capability of the form. Figure 9 shows the test bed.

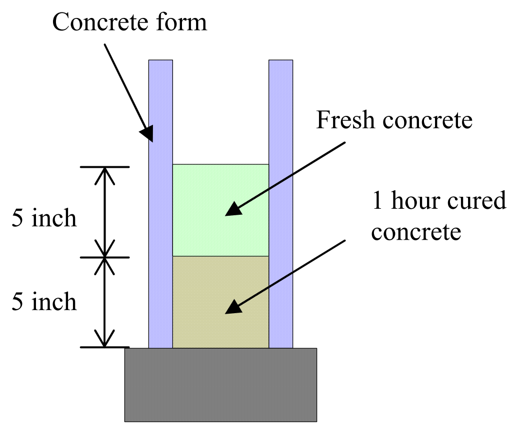


Fig. 8 Placing concrete procedures

Fig. 9 Pouring concrete in layer by layer

VII. RESULTS

As described in section VI-D, concrete was manually poured into the extruded form in 13 cm incremental depths (one hour intervals) to a final height of 60 cm (2ft). Figure 10 shows the finished wall. The compressive strength of this wall will vary depending on the type of concrete chosen. Concrete pouring in this demonstration, however, has been independent of the extrusion forming process. With more experimentation, the filling process can be synchronized with the extrusion process. The coupling of these two processes will depend on many factors including extrusion rate, pour rate, cure time and strength requirements. In the next generation CC system, the mechanical assembly for continuous concrete pouring will be integrated into the CC extrusion nozzle assembly.

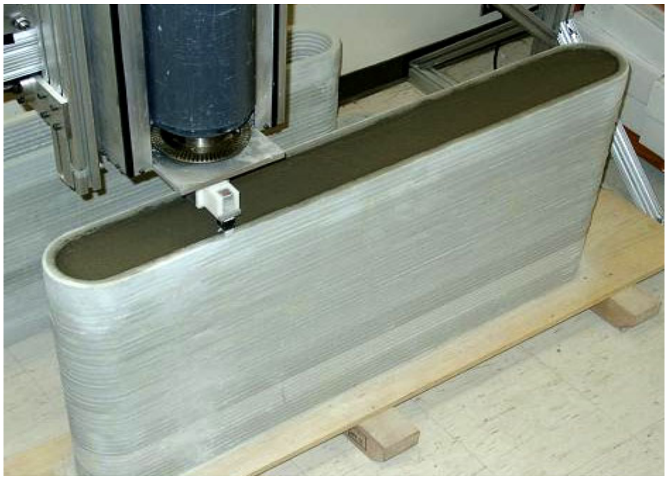


Fig. 10 A concrete wall made by CC machine

VIII. CONCLUSION

CC is a new innovative approach to solving problems facing the construction industry, particularly at the automation and process level. Currently available automated systems are geared toward conventional construction process and cannot fabricate complex structures nor adapt to sophisticated designs. To be successful, automated construction will require a paradigm shift in process technology. The CC technology fits in this category and has the potential to revolutionize the industry, changing it from the conventional "beam and post" paradigm to a layer by layer approach.

CC technology is scalable for building larger structures without difficulty. The corresponding cost increase and fabrication time compares well against other layer based manufacturing processes. Through this research we have shown that CC technology is capable of using commercially available, standard industry materials. CC therefore should be viewed as an immediately available technology, which can be extended to full-scale housing construction.

Note that due to mechanical speed limitations with the new CC system, CC construction speeds for realistic residential structures was not well established in this research. The CC construction speed is defined in terms of the material deposition rate in inches of concrete per hour. In the next generation CC system design, material deposition speed will be a carefully considered parameter. The goal of the next research phase is to erect a 3 meter (10 feet) concrete wall around a 200 m^2 housing unit within a single day.

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