

CONCRETE WALL FABRICATION BY CONTOUR CRAFTING

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Abstract: The feasibility of CC along with its unique capabilities and key performance characteristics (speed, surface quality, material variety, possibility of embedding reinforcement, etc...) have been demonstrated in the construction of relatively large geometrical shapes and structural components using a variety of construction materials. Construction and testing of full-scale concrete wall sections has been the goal of our recent project which this article reports.

Keywords: Contour Crafting; automation; construction; structures; dwellings; fabrication; rapid prototyping.

1. Introduction

Due to advances in sensing technology, numerical machine controllers, and automated drive systems, robotic systems have dramatically increased their performance, capability, and accuracy in recent years. Today robotic systems routinely replace many complicated, tedious, and dangerous human production activities in a variety of manufacturing applications.

During the last 18 years, construction automation and robotics have been implemented at various extents to address problems facing the construction industry such as productivity, quality, safety, high costs and skilled labor shortages in the United State and Japan [1]. The Japanese construction industry, in particular, is very active in automated construction research, seeking a solution to the skilled labor shortage. Many large Japanese construction companies have their own research centers with sophisticated equipment and large staffs researching new construction technologies. Kajima Corporation, for example, spends more than \$900M / year on construction research; a significant portion is invested in construction automation [2].

Approximately 89 single task construction robots have been prototyped and deployed in construction sites in Japan [3]. These single task robots replace simple human tasks thereby reducing labor costs and construction time. Automated construction systems such as AMURA, SMART and FACES are capable of fabricating high raised structures. These systems typically use precision fabricated components such as pillars, beams, ceilings, floor slabs and others [4].

However, the usage of single task robots is limited to small construction sectors mainly because the robots cannot detect and fix problems in real time

during operation. Also, fully automated construction systems do not allow much flexibility in the design of structures. The cross section of a structural member, for example, cannot be readily changed. A system capable of generating a variable cross section structure would be rather expensive. Furthermore, current automated systems require many prefabricated parts. This translates into extra costs for inventory, transportation, and additional machinery.

Using conventional automation technology, implementing a fully developed automated system that will address the problems facing the construction industry will be expensive. The following barriers hinder the efficient implementation of automation technology in construction [5]:

- Availability of feasible fabrication technologies for large scale products
- Conventional design approaches not suitable for automation
- Small production quantities compared to other industries
- Limitation of material choices
- High equipment costs and maintenance fees
- Management issues

Previous attempts at developing automated construction systems have not adequately addressed these barriers. Current available automation technologies and engineering know-how may not be sufficient to overcome these barriers cost effectively. The construction industry could seek alternate approaches to existing fabrication and assembly processes. The new approach should consider adaptability to automated construction technologies and processes.

In recent years rapid prototyping (RP) processes have been implemented in a variety of applications

and disciplines such as architecture, automobile design, aerospace and medical industries. RP processes are capable of fabricating complex structures, as shown in Fig. 1. However, RP systems today are not suitable for fabrication of larger scale parts. A special RP technology developed at the University of Southern California (USC) is Contour Crafting, which was introduced at the 19th International Symposium on Automation and Robotics in Construction (ISARC) in 2002. CC technology adapts RP capabilities and extends them to the field of large scale construction. As in other RP methods, in Contour Crafting (CC) material is added layer by layer according to a computer control sequence.



Figure 1. A complex geometry (Hagia Sophia in Istanbul) fabricated by a RP process
[Source: MIT 3DP Laboratory]

CC is suitable for rapid fabrication of large-scale complex shaped objects with smooth surface finish. The CC extrusion and filling process is shown in Figure 2.

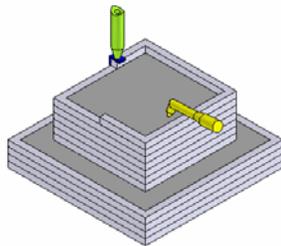


Figure 2. Extrusion and Filling Process

The extrusion process forms the smooth object surface by constraining the extruded flow in the vertical and horizontal directions by the use of trowels. A schematic view of extrusion using a single nozzle is shown on the left side of Figure 3. The orientation of the side-trowel is dynamically changed for better surface fit for each decomposed layer. The side-trowel allows thicker material deposition while maintaining high surface finish. Thicker material deposition cuts down fabrication time, which is essential for building large-scale parts by using the additive process. Maximum deposition layer thickness is limited by the trowel height.

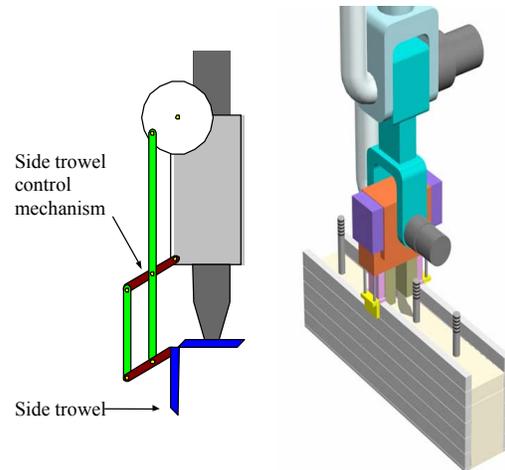


Figure 3. CC single nozzle (left) and multiple nozzle assemblies.

On the right side of Figure 3 a compound nozzle assembly is shown by which concurrent extrusion of two wall sides and filling of the previously built layer may be performed. As the extrusion nozzle moves according to the predefined material deposition path of each layer, the rims (smooth outer and top surface of outside edges) are first created. The troweled outer surface of each layer determines the surface finish quality of the object. The smooth top surface of each layer is also important for building a strong bond with the next layer above. Once the boundaries of each layer are created, the filling process begins and material is poured or injected to fill the internal volume. For viewing several animations of the CC process please refer to www.contourcrafting.org.

3. Current state of research and development

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

3.1 Hardware system design

A special simplified CC nozzle system and a three axis motion control mechanism have been developed for demonstration of full scale wall construction. The new CC system, shown in Figure 4, consists of an extrusion system that conveys a mortar mixture from the material reservoir and deposits it in controllable amounts to form a desired shape. A piston is attached to and driven by the lead screw which turns at constant rotational speed upon extruding the mixture. As the mortar exits the

extrusion nozzle, the machine moves the nozzle assembly in the X-direction at pre-specified speed.

extruded form becomes an integral part of the wall.

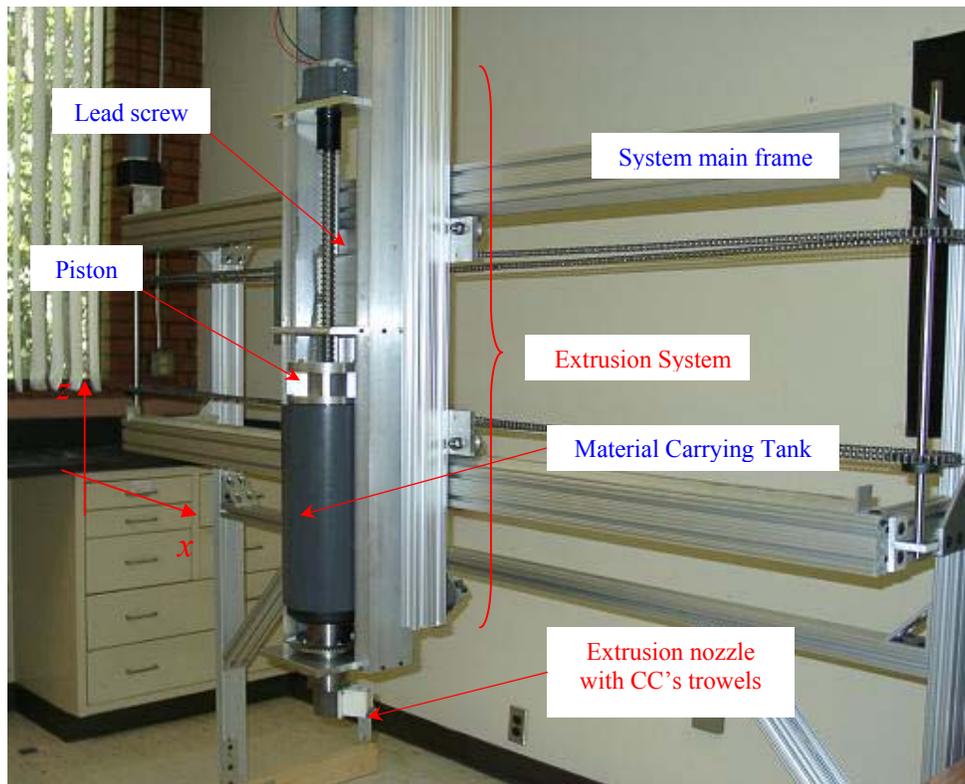


Figure 4. A picture of a new CC machine for fabricating a concrete wall

Once the extrusion system finishes its single layer cycle, the entire extrusion system moves vertically an incremental distance equal to the height of the next layer. The cycle is repeated until the final shape of the boundary is established. The machine structure supports and precisely guides the entire extrusion system during fabrication. The machine frame has two V-shape profiles that are used as a rail to guide the extrusion system. The current frame permits extrusion only in the X and Z directions, therefore is limited in the types of 3-D objects that can be created.

The extruded boundary establishes both the internal and external surface finish which plays a key role in the appearance of the finished product.

3.2 Target geometry

To reproduce a full scale concrete wall segment, the geometric specifications of a typical concrete wall used in housing construction was pre-programmed. Figure 5 details the wall specifications and dimensions. The concrete form is first fabricated by extruding the material in incremental vertical layers of 19 mm (0.75") in width and 13 mm (0.5") in height. The final concrete form is a hollow wall structure with a curved radius at each end. Following the boundary extrusion, any type of concrete can be poured in as filler structural material either manually or automatically with the CC machine. Filling the inside space with concrete may be also done in a layer-by-layer fashion. After the concrete sets, the

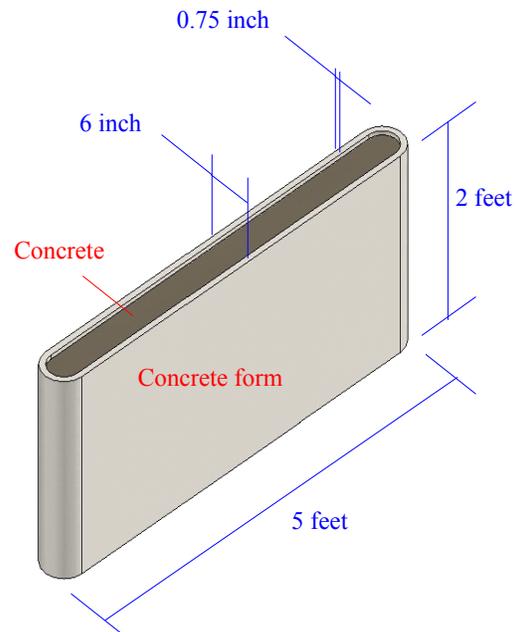


Figure 5. A schematic view of target concrete wall

3.3 CC Nozzle Assembly

To fabricate the target geometry a new CC nozzle system was designed and integrated with a new CC machine. Unlike previous designs, the new CC nozzle is equipped with dual trowels to control both the internal and external surface finish of the extruded rims. Figure 6 shows the new CC nozzle assembly. The nozzle assembly is offset 70mm (2.75") from the flow center of the extrusion system.

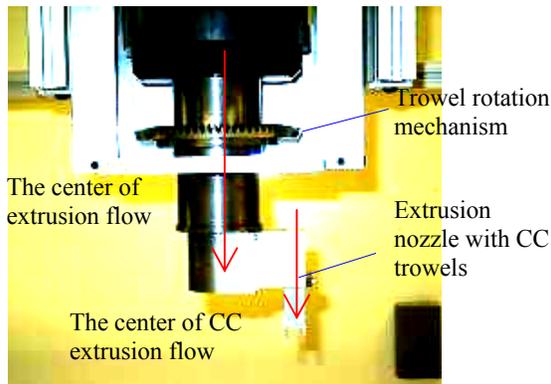


Figure 6. A closer view of CC nozzle with trowels

To fabricate the rounded ends, extrusion in the X-direction is stopped and the assembly is rotated 180 degrees. With this configuration the Y axis is not used, hence reducing the machine complexity at the cost of being limited to fabrication of straight wall sections.

4. Fabrication of a Concrete Wall

The success in fabricating a part using the CC process mostly depends on the extruded material characteristic. Any paste-like material that can be extruded using conventional tooling can also be used in Contour Crafting..

4.1 Mortar Mixture and its Compressive Strength

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

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

To verify its early compressive strength, three cylindrical test specimens, 5 cm X 10 cm (2" X 4") were made and cured for 7 days in room temperature. Tests were conducted at USC's Civil Engineering structural testing laboratory with the results shown in Table 1.

Table 1. Results of testing compressive strength

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

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

4.2 Fabrication

The mortar mixture was prepared using power drill driven mixing paddles and was loaded into the material carrying tank, shown in Figure 4. The velocity of the extrusion system in the horizontal direction was set to 20 mm/sec with stabilized continuous extrusion flow from the CC nozzle assembly. Initial extrusion flow is discarded until the flow is stabilized and the system starts its fabrication. Once an entire batch of the mortar mixture loaded inside the material carrying tank is used up, the CC system pauses until another batch of mortar is loaded and the extrusion continues to form the remaining concrete form. A batch of mortar is consumed in approximately 10 minutes and yields a concrete form approximately 64 mm (2.5") high. To complete the target geometry shown in Figure 5, nine batches were needed. The final concrete form fabricated by the CC system exceeded a height of 60 cm (2 feet) and is shown in Figure 7.

4.3 Lateral Pressure on Concrete Form

The function of the concrete form is to contain freshly poured concrete in a contained mold until the placed concrete sets. Lateral pressure against the concrete form is a function of the height and mass of the poured concrete; the pressure is not affected by the wall thickness. The following is a standard formula widely used as a design guide for vertical formwork based on ACI standard 347:

$$P=W*H$$

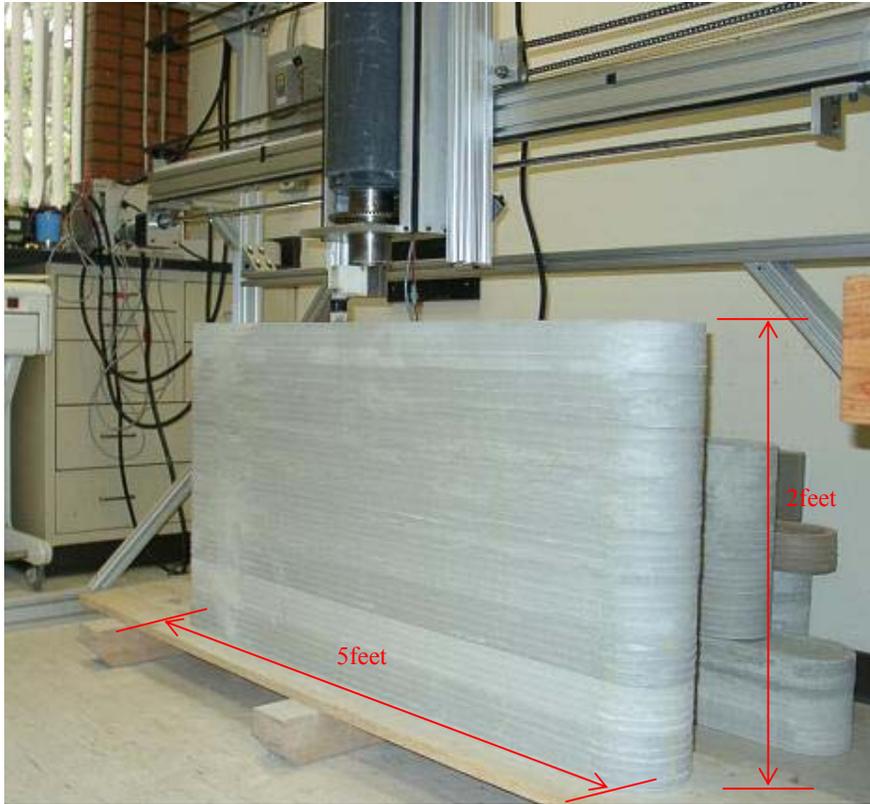


Figure 7. A concrete form of desired span and height fabricated by the CC machine

Where: P = Lateral pressure
 W = Unit weight of fresh concrete or 150 pcf
 for normal weight concrete
 H= Depth of fresh concrete

Table 2. Concrete pressure for wall form

Pour rate (ft/hr)	Pressures of Vibrated Concrete (psf)	
	50°F	70°F
1	330	280
2	510	410
3	690	540
4	870	660
5	1,050	790
6	1,230	920
7	1,410	1,050
8	1,470	1,090
9	1,520	1,130
10	1,580	1,170

Some approximated lateral pressures are in Table 2. These are design guides for wall concrete for mwork. The actual pressures may vary. Note that reliable data is difficult to obtain in published references when the pour rate is less than 1 ft / hr.

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

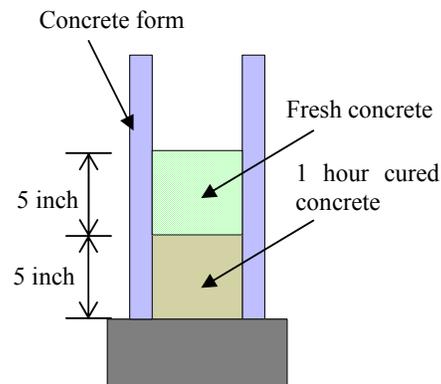


Figure 8. Placing concrete procedures

The bottom cross-hatched section represents concrete which has been cured for one hour. The cured concrete produces minimal lateral pressure on the

form but the exact value was difficult to quantify in our experiments. Data was not available in the available literature; therefore, a simple test was devised to validate the strength capability of the form. Figure 9 shows the test bed.



Figure 9. Pouring concrete in layer by layer

A batch of concrete was poured to a height of 13 cm (5"). The second batch was poured on top of the first batch after one hour without problems. The test procedure, if repeated 24 times, will result in the erection of a 10 feet high "conventional" concrete wall in 24 hours. Ten feet is a standard height for concrete walls in residential housing construction.

5. Results

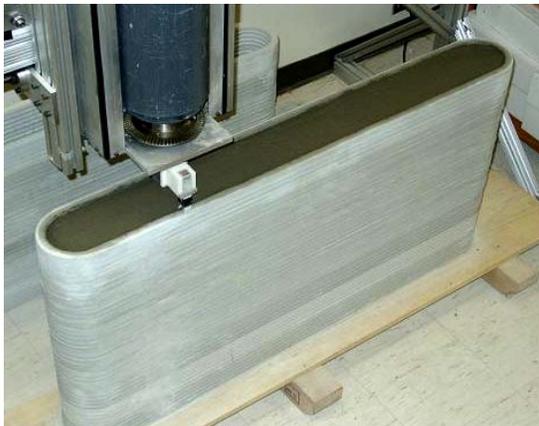


Figure 10. A concrete wall made by CC machine

As described in section 4, concrete was manually poured into the extruded form in 13 cm incremental depths (one hour intervals) to a final height of 60 cm (2ft). Figure 10 shows the finished wall. The compressive strength of this wall will vary depending on the type of concrete chosen. Concrete pouring in this demonstration, however, has been independent of the extrusion forming process. With more experimentation, the filling process can be synchronized with the extrusion process. The coupling of these two processes will depend on many factors including extrusion rate, pour rate, cure

time and strength requirements. In the next generation CC system, the mechanical assembly for continuous concrete pouring will be integrated into the CC extrusion nozzle assembly.

5. Conclusion

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

The CC technology is one that is scalable to fabricate larger parts without difficulty. The corresponding increase in cost or fabrication time compares well to other layer based manufacturing processes. Through this research we have shown that the CC technology is capable of using even standard industry materials. CC may hence be regarded as an immediately available technology which can be extended to full-scale housing construction.

Note that due to mechanical speed limitations with the new CC system, actual material deposition speed was not well established in this research. In the next generation CC system design, material deposition speed will be a carefully considered parameter. The goal of the next research phase is to erect a 3 meter (10 feet) concrete wall around a 200 m² housing unit within a single day.

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