Mega-scale fabrication by contour crafting

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Abstract: Contour Crafting is a mega scale layered fabrication process which builds large scale three-dimensional parts by depositing paste materials layer by layer at unprecedented speed and with superior surface quality. This paper presents an overview of related research activities and the progress aimed at extending the technology to construction of residential housing units and civil structures.

Keywords: contour crafting; layered manufacturing process; mega scale fabrication; cement extrusion; construction automation; house construction; lunar construction.

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Biographical notes: Behrokh Khoshnevis is a Professor of Industrial and Systems Engineering and is the Director of the Center for Rapid Automated Fabrication Technologies (CRAFT) at USC. He is active in CAD/CAM, robotics, and mechatronics related research that concern 3 fabrication processes called *Contour Crafting*, *SIS and MPM*, development of biomedical systems, autonomous mobile and modular robots for assembly applications on earth and in space, and automated equipment for oil and gas industries. He is a Senior Member of the Society of Manufacturing Engineers, a Fellow Member of the Society for Computer Simulation and a Fellow Member of the Institute of Industrial Engineers.

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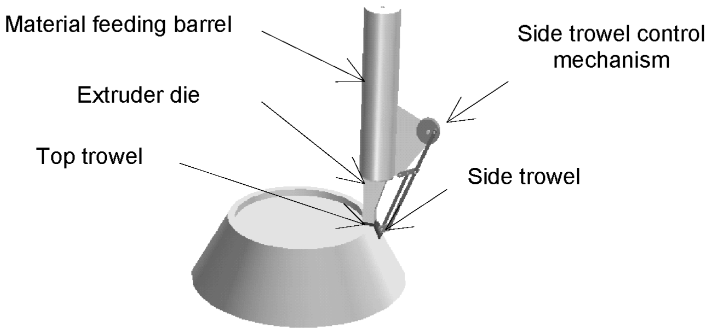
1 Introduction

Contour crafting (CC) is a method of layered manufacturing (LM) process that uses polymer, ceramic slurry, cement, and a variety of other materials and mixes to build large scale objects with smooth surface finish (Khoshnevis, 1998). Other key advantages of CC are faster fabrication speed and possibility of integration with other robotics methods for installing internal components such as pipes, electrical conductors, and reinforcement modules to enhance mechanical property (Kwon, 2002). A schematic view of the CC extrusion assembly is shown in Figure 1.

Figure 1 Schematic view of CC extrusion assembly



The extrusion process forms the smooth surface of the object by constraining the extruded flow in the vertical and horizontal direction to trowel surfaces. The orientation of the side trowel is dynamically controlled to conform to the slope of surface features. The side trowel allows for thicker material deposition while maintaining smooth surface finish. Use of thick layers by other LM processes is not possible because rough surfaces with stair casing effect will be resulted, especially for slant and curved surfaces. Furthermore, in most processes thick deposition is physically not possible (e.g., adhesive liquid or laser cannot penetrate too deep into powder in a controlled manner).

Thicker material deposition cuts down fabrication time, which is essential for building large scale objects. In CC maximum layer height is limited by the side trowel height. As the extrusion unit moves according to the predetermined mateiral deposition path for each layer, the smooth outer and top surfaces of each layer rim are first created, followed by the filling process which fills the internal volume with material either by pouring or injection.

2 Research progress

Contour Crafting (CC) has been the focus of intensive research at the USC Center for Rapid Automated Fabrication Technologies (CRAFT). Various materials for various applications have been tested and evaluated to date. Most of the current research effort is directed at the application of the technology in construction. The following sections are organised according to the classes of materials used in research.

2.1 Ceramic materials

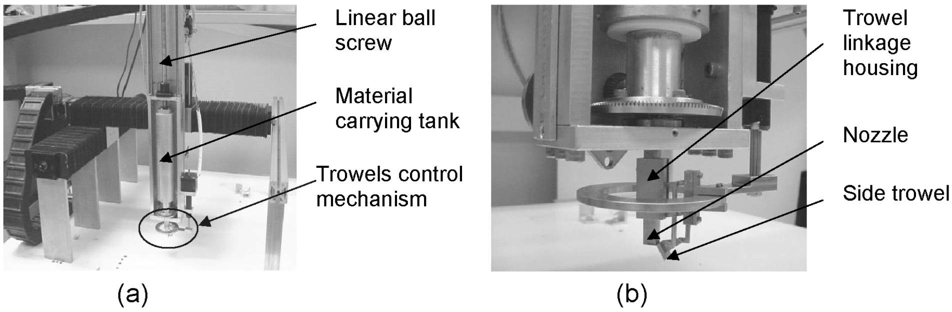
Clay is a ceramic material which is aboundant in nature and hence it has been used since the dawn of civilisation for creating various objects with or without thermal treatment. Clay has been used in uncured form as clay bricks in construction. Sintered clay has been used for pottery and tiles for many centuries. More recently, ceramic material are finding advanced applications in manufacturing. Ceramics processing usually starts with ceramic paste the property of which is influenced by its mineral and structural composition, and by the amount of water that it contains.

Mechanical properties of ceramic paste primarily depend on the water content. With sufficient water the paste softens and forms slurry that behaves as a viscous and formable liquid. When the water content is gradually reduced by drying, the ceramic paste loses its plastic state property and holds together resisting deformations. Ceramic paste shrinks and its stiffness increases until it becomes brittle with further loss of water and enters the semisolid state. By drying continuously, the clay reaches a constant minimum volume at its solid state.

2.2 CC machine structure for ceramics processing

An assembled CC machine for ceramics processing is shown in Figure 2. The machine mainly consists of an extrusion unit and the trowel control mechanism. The extrusion unit carries uncured ceramic paste into material carrying tank and a linear ball screw driven piston pushes the paste through a CC extrusion nozzle. With controlled rotational speed of feeding motor, stabilised extrusion flow can be achieved. When complex shape of geometry is being fabricated, the system controls the angle and orientation of the side trowel to conform to outside surface geometry each cross sectional layers.

Figure 2 System configurations for ceramic part fabrications; (a) CC extruder sits on an x-y-z gantry robot and (b) details of CC nozzle assembly



2.3 Preparing ceramic paste

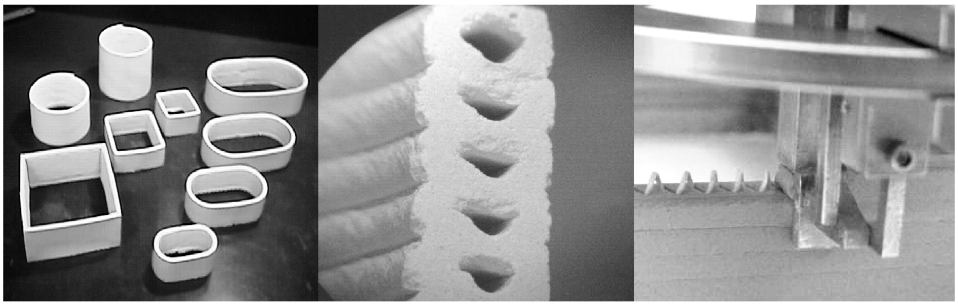
The ceramic material (clay) used in our experiments was procured from America Ware Company in Los Angeles. The clay contained: Pioneer Talc 2882, Taylor Ball clay, Barium Carbonate, Soda Ash, Sodium Silicate, and 35% water by mass. The clay parts were fabricated at room temperature and then bisque-fired in a kiln at 1063°C~1066°C for 10 hours. For glazing, a second firing at 1003°C was carried out for 8~9 hours. Forced drying by heating and the wax-coating procedure were not necessary due to the higher structural wet strength of the clay material. Large parts could be made with the assurance that the clay would not sag or collapse inward.

A way of loading clay into material carrying tank was devised in order to avoid entrapping air inside the tank. Entrapped air typically causes some defect modes at fabricated parts as forms of voids, excessive dry shrinkage, weak structural integrity, etc. A filling method was devised using a funnel shape apparatus that enabled continuous insertion of clay into the tank and pre-extrusion processing of the material also seemed to significantly reduced the void and defect surface formations.

2.4 Fabricated ceramic parts

Several pre-designed experiments were conducted to study the feasibility of CC construction process by fabricating various geometries, creating hollow depositions by application of mandrills inside the CC nozzle, and trying various concurrent processes including imbedding of reinforcement material such as steel coils. Figure 3 shows the some results of these trials. The experimentation with ceramic materials has demonstrated the possibility of applying the CC process to the field of construction.

Figure 3 Demonstrations of CC constructability; (left) simple geometries, (middle) cross section of the fabricated part revealing hollow depositions, and (right) metal coil imbedding



3 Construction automation

The construction industry is facing several problems including low productivity, poor quality, low safety, and skilled labour shortage (John and Hiroshi, 1996). In the last three decdes primarily some Japanese construction companies have attempted to remedy the shortage of skilled labour by resorting to automation. As a result more than 89 single task construction robots and 11 full automated construction systems have been prototyped and implemented in the Japanese construction fields. However, the benefits of construction automation has not been significant compared to what has been experienced in the manufacturing industry (Khoshnevis, 2004). Implementation of automation in construction is prohibitively expensive due to the extraordinary complexity of automating a large number of various operations which generally involve large scale and heavy objects.

Currently there are two categories of automation considered by the Japanese construction companies. The first uses single task robots that can replace simple labour activities at the construction sites. Single task robots can be classified by four different types- concrete floor finishing, spray painting, tile inspection, and material handling.

The second category consists of fully automated systems that can construct high raised steel buildings or steel reinforced concrete buildings using prefabricated components. An example of this approach is Big-Canopy, which is the world’s first automated construction system for building a precisely defined concrete structure and has four independent masts supporting an overhead crane which delivers components at the control of a simple joystick. All tasks are scheduled and controlled by a centralised information control system.

The introduction of robotics 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 (such as using a brick laying robot) is invariably expensive, hence the associated cost saving is minimal. Fast changing construction requirements and project complexities create complicated requirements and exceptional challenges for automation technology to meet.

Layered fabrication, which has been used for several millennia in manual construction, has become a new fabrication alternative in manufacturing. Contour Crafting as a large-scale layered fabrication approach represents a revolutionary paradigm in automation for the construction industry. CC replaces conventional 'cast-in-place' method with a layer-by-layer approach. This new way of thinking offers automation a much better chance to penetrate and succeed in the construction field (Hwang, 2005).

3.1 Simple CC formwork systems

As the first step in demonstrating the potential of CC in construction, a concrete wall section has been built using the process. Concrete walls are ususally built using forms. A concrete wall form typically consists of sheathing, studs, wales, ties, and bracing as shown in Figure 4. A closer section of a traditional wall form is shown in Figure 5(a). The fresh concrete is confined to the sheathing and places a lateral pressure on the sheathing until the concrete is cured.

Figure 4 Schematic of conventional formwork system for vertical concrete wall

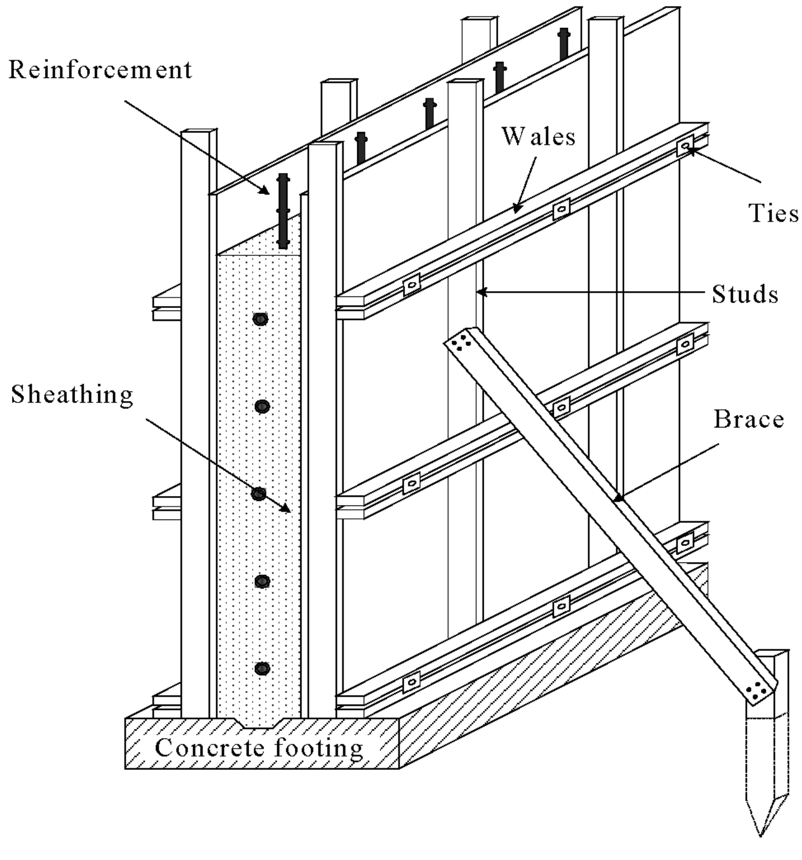
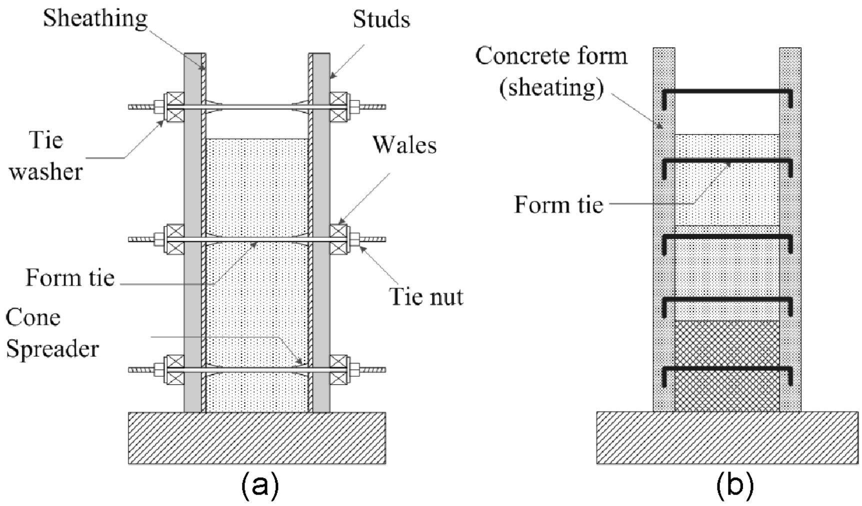


Figure 5 Closer sections of wall forms; (a) traditional wall form and (b) CC wall form



Due to high lateral pressures, the sheathing is supported by properly spaced studs and wales to prevent any displacements. The tie rod is secured with nuts and washers to retain the wales and prevent bulging. The spreaders also help to maintain uniform wall thickness. After the concrete sets, the exposed part of the tie rod can be removed or kept in place as an integral part of the wall. The spreaders can also be removed or kept in place and mortar can be used to backfill the voids in the concrete if necessary.

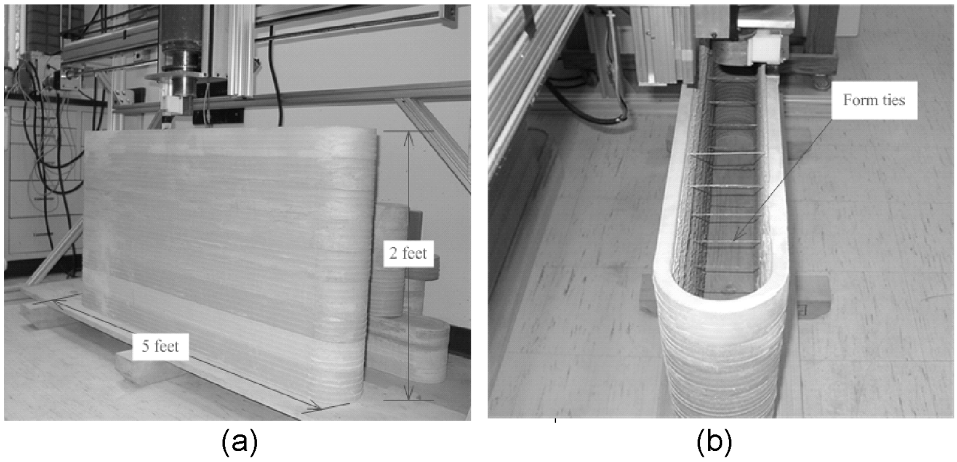
For the CC formwork design (Figure 5(b)) side walls (forms) are constructed using mortar and secured with U-shaped tie rods. This new formwork is simpler than the traditional design since it uses only two components: sheathing and tie. Sheathing is created in position by adding mortar continuously according to pre-defined material deposition sequence; the ties are inserted at the sheathing locations. The sheathing physical properties could be inferior to that constructed according to the traditional formwork system. The advantage however is that the new formwork can be constructed without using separate formwork materials. If the pour rate is less than 5 inch per hour (13 cm/hour), the lateral pressure is minimal and ridge formwork materials are not necessary. Sheathing and ties are kept in place as an integral part of the concrete wall after hardening.

3.2 Fabrication of vertical concrete formwork

The mortar mixture was prepared using power driven mixing paddles and loaded into the material carrying tank. The initial extrusion flow during start up is discarded until the flow is stabilised and the system starts its fabrication. Once an entire batch of the mortar mixture inside the material carrying tank is consumed, the CC system pauses until another batch is loaded. Extrusion then continues to complete the remaining concrete form. A batch of mortar is consumed in approximately 10 minutes and yields a concrete form approximately 2.5 inch (64 mm) high.

Custom made form ties are manually inserted between layers while the CC machine is actively fabricating the concrete wall form. A tie is inserted at every 12 inches horizontally and 5 inches vertically. To complete a prototype section of full-scale concrete wall section nine batches were prepared. The final concrete form exceeded a height of 3 feet (60 cm) and is shown in Figure 6.

Figure 6 A concrete wall form fabricated by the CC machine: (a) designed span and height of concrete wall form and (b) inserted form CC form ties



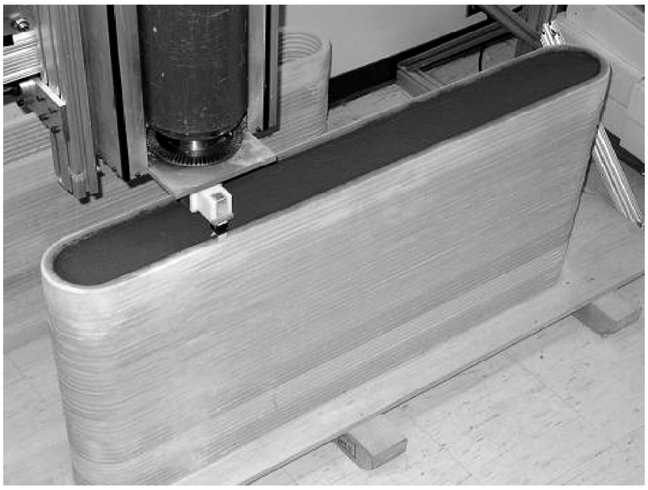
3.3 Placing fresh concrete

Commercial concrete construction processing consists of mixing, transporting, and placing of the concrete. Truck-mixing is used in most construction fields. Concrete is transported with belt conveyers, buckets, and chutes depending on the construction field site and structure design. After the concrete is placed, it is compacted within the forms to remove lumps or voids. Hand tools or mechanical vibrators are used to guarantee a uniform dense structure.

In the CC process, placing concrete requires different procedures. A batch of concrete is poured to a height of 5 inch (13 cm) and a second batch is poured on top of the first batch after one hour. A one hour delay batch is sufficient to control the lateral pressure of the concrete by allowing it to partially cure and harden. Even using one hour delay, it is possible to erect 10 foot high concrete walls in a day. The time delay needs to be adjusted depending on the concrete hardening rate. Accelerators chemicals may be added when higher concrete placing rates are needed.

As described in Section 3.5, concrete was manually poured into the extruded form in 13 cm incremental depths to a final height of 60 cm (2 ft). Figure 7 shows the finished wall.

Figure 7 A concrete wall made by CC machine



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 synchronised with the extrusion process. The coupling of these two processes will depend on many factors including extrusion rate, pour rate, curing 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.

4 Information technology issues in mega-scale fabrication

Manufacturing advances in Mega-Scale Fabrication (MSF) offers the potential of constructing full-scale buildings directly from 3D CAD models. However, this vision of automated end-to-end construction process presents tremendous challenges to the development of the underlying information technology infrastructure. Current industry practices divides and separates the construction tasks among several disciplines; an integrate framework is needed to combine and unify tasks from the disciplines of architecture, engineering, construction, logistics and inspection. This framework must provide the geometric modelling expressiveness desired by architects to represent their creative designs and by customers to individualise their buildings. Yet, it also must provide guidance and constraints imposed by the limitations of the fabrication process to allow only feasible designs. This feasibility analysis must be constructive (as opposed to pure existence proofs). As part of the analysis it must generate a fabrication plan detailing the manufacturing sequence steps needed to construct the design artifact. In addition, the speed at which MSF can operate exacerbates the potential construction delays. Logistics plans and schedules must be automatically generated, and they must be tightly coupled with the fabrication plans. Because of the unprecedented speed of CC construction, attendant improvements in the construction inspection process will be required. Developments are needed in advanced sensory systems and information technologies for automated real-time inspection.

4.1 Design validation and process planning

The input to the MSF system is the architectural CAD design. This CAD geometry can be viewed as an abstract description of the construction task. The outputs of the MSF system are sequences of detailed primitive robot actuation tasks that, if executed by appropriate robots and within the appropriate environment, will build the house as specified by the CAD geometry. The work that the MSF system has to do is to find a way to transform the abstract CAD task to the robot actuation tasks. The basic approach of the MSF system is to apply a series of abstraction refinement operators that successively decompose tasks into more manageable sub-tasks, and successively incorporate new constraints to ensure constructability.

4.2 Analysis of MSF feasibility

In terrestrial environments, MSF feasibility is primarily a function of gravity and the building material (adhesive properties, curing rate, and so on). MSF technology builds a house by extruding building material one layer at a time. The primary constraint on building geometry is that during the construction process the layers underneath be able to support the layers above. We call the set of paths that an extruder nozzle needs to traverse a layering of the geometry and the union of all the layers the layering task graph. This analysis module determines feasibility by generating a feasible layering task graph. If it fails it will warn the architecture by indicating where and why it failed. As we shall see, not all layering task graphs lead to feasible structures.

A complete comprehensive feasibility evaluation involves reasoning with geometry, physics, chemistry, and construction process. Our hypothesis is that, once a few physical parameters have been measured and restated as geometrical constraints, building feasibility can be transformed into a geometric reasoning problem. At this level of analysis we ignore the time dimension, and assume the materials are always cured properly. This hypothesis is consistent with current building code and practices (e.g., building codes specify maximum spacing between wall studs and thickness of roof sheeting). The upper layers of material generate forces on the layers below. If the successive layers are deposited at an offset with a curvature, then a bending force is generated. This type of physical constraint translates into a geometric constraint on curvature in the direction of gravity and weight. Another type of physical constraint that may play an important role is slippage, which translates into a geometrical constraint on maximum angle of incline of the layer.

The most straight-forward approach to layer geometry is to define a series of horizontal x-y cutting planes (Figure 8(a)). The intersections of the cutting planes define the paths that the extrusion nozzle must traverse to incrementally construct the building from the ground up. Horizontal cutting planes tend to work well for two-and-half dimensional geometries (e.g., vertical walls), and even for some domes with low curvature (Figure 8(b)). For domes and other geometries with high curvature, horizontal cutting planes may violate the curvature-weight constraint. In this case, inclined cutting planes can be used to form inclined arches and distribute the weight sideways (Figure 8(c)). During construction to provide extra support the arches may be required to be built from two pieces from bottom to up. For organic geometries, non-planar cutting surfaces may provide more efficient layering. Given a building with complex geometries, more than one type of cutting surfaces may be needed. For the building shown in Figure 8(d) and 8(e), horizontal cutting planes are used for the walls. However, the curvature and orientation of the roof surface requires the use of inclined cutting planes. Figure 9 shows other vaulted roof structures that require inclined cutting planes. In general this requires a partitioning of the building surfaces into sub-surfaces by the type of cutting surfaces, where each cutting surface type is tailored to that sub-surface. This partitioning problem has similarities to the surface partitioning problem for grid generation that one of the authors of the proposal has worked with before. In both problems, the surfaces have to be partitioned according to geometric constraints that ultimately are based on deeper constraints. In contour crafting, a deeper constraint is to ensure building feasibility. In grid generation the deeper constraint is to minimise simulation numerical error, see (Yao and Gelsey, 1994, 1996).

Figure 8 Layerings of various geometries for contour crafting construction

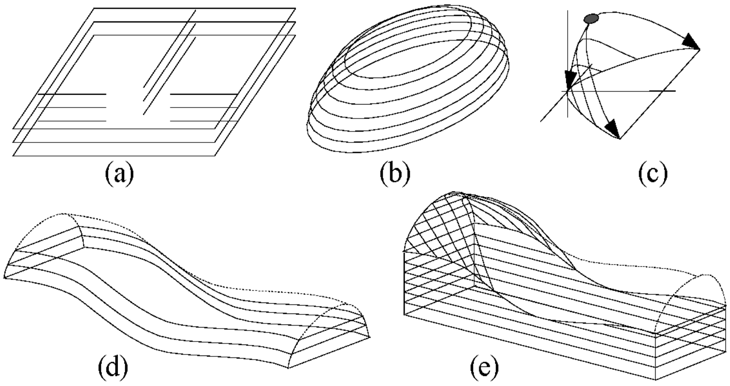
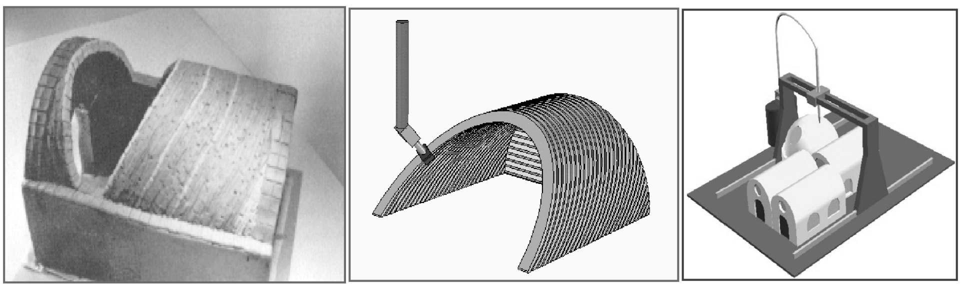


Figure 9 Manual vault roof construction and implementation by CC



4.3 Automatic generation of sacrificial supports

Some structures cannot be constructed without sacrificial support. For example, depending on the material properties (tensile strength and interlayer adhesiveness) and arch geometry (span, rise and thickness), certain arches will collapse during the contour crafting construction process without external support. However, once completed (with the equivalence of keystone inserted) arches are very stable load-bearing structures.

Sacrificial supports contribute to construction waste, and they may need to be manually removed after construction. The goal of this reasoning module is to design sacrificial supports that

- reduce stresses that cause breakages and deformations
- minimise the material and time used to construct the sacrificial supports.

In most cases we envision sacrificial support being constructed with the same MSF process. Similar to the actual structure, sacrificial geometries are layered with cutting planes/surfaces and extruded. The boundary surface intersecting the sacrificial support and the actual structure may be sprayed with wax, or similar substances, to facilitate their later removal.

In Figure 10 the left and middle figures depict sacrificial supports constructed entirely from the MSF process. The leftmost figure depicts a complete sacrificial wall. The middle figure depicts multiple columns. Sacrificial columns are potentially more desirable, because they require less material. The rightmost figure depicts the use a pre-fabricated sacrificial lintel. The lintel braces the two legs of the arch against each other, and it helps to transfer the force downward along the legs. In this design additional robotic grippers need to be attached to the MSF machine to lift and put the lintel in place. Also, notches need to be created in the legs to accommodate the lintel. Once the lintel is in place, the MSF nozzle can extrude the sacrificial wedge to support the top portion of the arch. This sacrificial lintel design is similar to the sacrificial truss used during the construction of the St. Louis Gateway Arch. See Figure 11.

Figure 10 Possible sacrificial support types used during the construction process to support partially completed arches

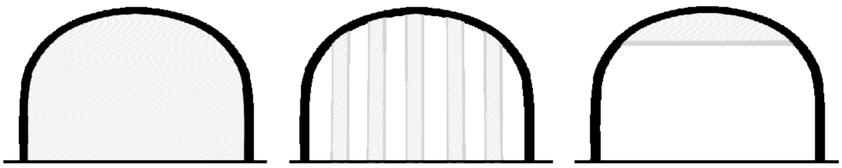


Figure 11 St. Louis gateway arch with sacrificial truss

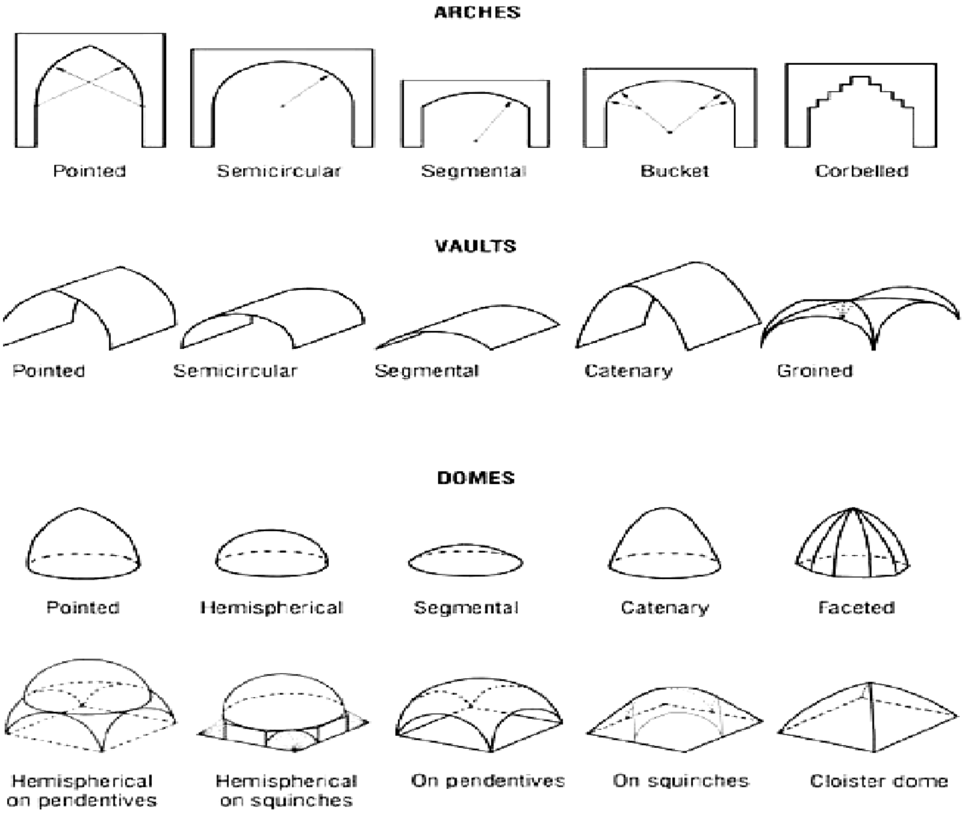
4.4 Designer's handbook and compound geometries

Each fabrication process offers its own set of unique strength and constraints. Geometries feasible using one technique may be impossible to build under another. Innovative manufacturing steps may need to be developed to realise creative designs. A designer's handbook offers a potential way to guide the architect toward feasible designs, and to record fabrication plans for manufacturing reuse.

The design of vaulted structures can be intricate and complex, see Figure 12. However, these structures are made up of basically three primitive design elements: arches, vaults and domes. See Figure 13 for a sample catalog of these design elements. In the context of CC using the previous feasibility analysis and sacrificial support analysis modules, designer's handbook cataloging can be developed with the various feasible vaulted design elements. In addition scaling rules, parameterised by appropriate material properties and load conditions, can be developed to allow architects to instantiate vaulted design elements to the appropriate dimensions. These scaling rules may either be derived mathematically. Or, off-the-shelf structural finite element analysis packages, such as Nastran, may be used to perform systematic parametric studies. For example, a sample scaling rule on arches would require thicker columns for the semicircular arches than the catenary arches. For a catenary arch, the line of thrust traverses through its center. A semicircular arch needs extra thickness to offset the lateral thrust. Otherwise, the semicircular arch would buckle along its haunches.

Figure 12 Examples of compound vaulted structures from CalEarth

Figure 13 Sample vaulted design elements from Aurovile Earth institute



Building on top of off-the-shelf CAD systems, such as ArchiCAD, we can provide tools to allow architects to design complex vaulted structures by composing them from primitive design elements. From a palette of primitive design elements, the architect can select and drag multiple design elements on to canvas. These design elements can be resized and repositioned as needed. Then, these design elements are combined using Boolean operations similar to Constructive Solid Geometry (CSG), such as union, intersection and difference.

There are two advantages in using this CSG-like representation. One advantage is that it can be used to provide quick feedback on the structural appropriateness of the design. Of course, detailed structural properties of complex compound vaulted structures may be difficult to predict without resorting to finite element analysis. However, we can perform quick calculations and simple checks on the design base on knowledge of the primitive vaulted elements. For example, the common column shared by two adjacent arches has to support twice as much downward force. Also, if the two adjacent arches are co-planer, then the lateral forces counteract each other to prevent buckling at the haunches. Another advantage is that the representation may provide hints as to how to construct sacrificial supports. For example, let’s assume the architect designs an igloo-shaped structure, a semicircular dome structure with a semicircular vault entrance. With a sufficiently larger structure, the vault entrance cannot be constructed using MSF, unless there is sacrificial support at one end of the vault. In this case, it may make sense to construct the support at the dome end of the vault using the part of the dome underneath the vault, because it also helps to support the dome during construction.

4.5 Trowel path planning and nozzle control

This level of analysis reasons about the ability to physically realise the layering task graph by specifying the trowel path, trowel/nozzle orientation, and nozzle flow control. At this level the constraints include collision avoidance of trowel/nozzle assembly with previously built portion of the structure, and minimisation of layering imperfections (such as bulges, gaps and cracks). Again, we can potentially reduce these constraints to geometric reasoning problems by breaking each layering into smaller segments and analysing each segment.

To extrude layers of even thickness, the volume of material extruded by the nozzle should be proportional to the speed at which the nozzle is displaced. Also, as the nozzle moves and extrudes, the trowel orientation must be tangent to the layering path at all times in order to form smooth surfaces. For straight or smoothly curved segments trowel orientation adjustments should be readily achievable.

Reasoning about corners. When the trowel reaches a corner it must change its orientation to be tangent to the opposite side of that corner. At such times the nozzle stops extruding as the trowel rotates and then pushes in the extruded material from the opposite edge, see Figure 14. However, the *push-in* technique tends to create bulges around sharp acute corners, because of excess material. The nozzle has to reduce its flow rate as it approaches the corner, see Figure 15. The exact amount of material reduction can be computed based on the angle of the corner and the geometry of the nozzle.

Figure 14 Trowel path planning and nozzle control around convex corners

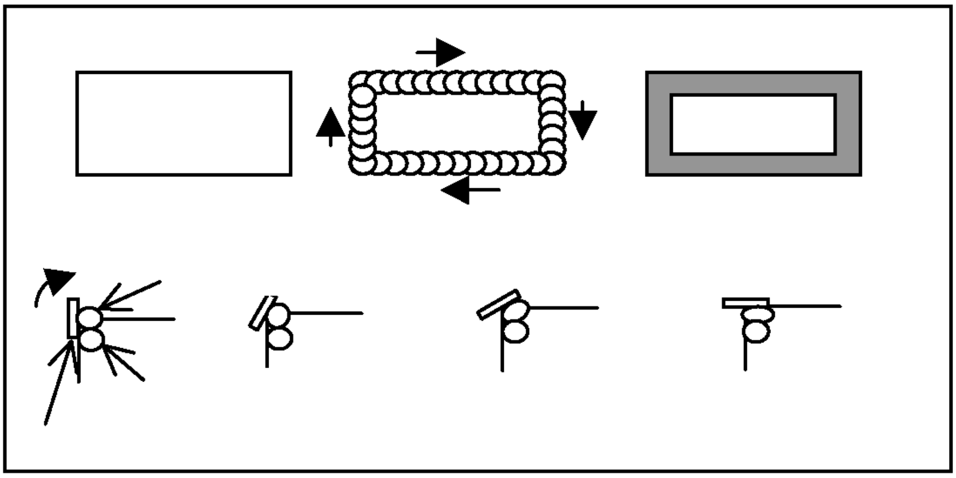
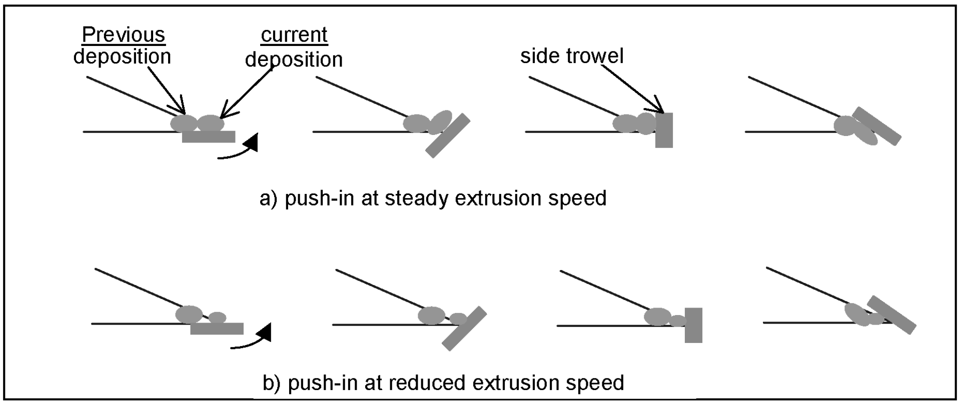
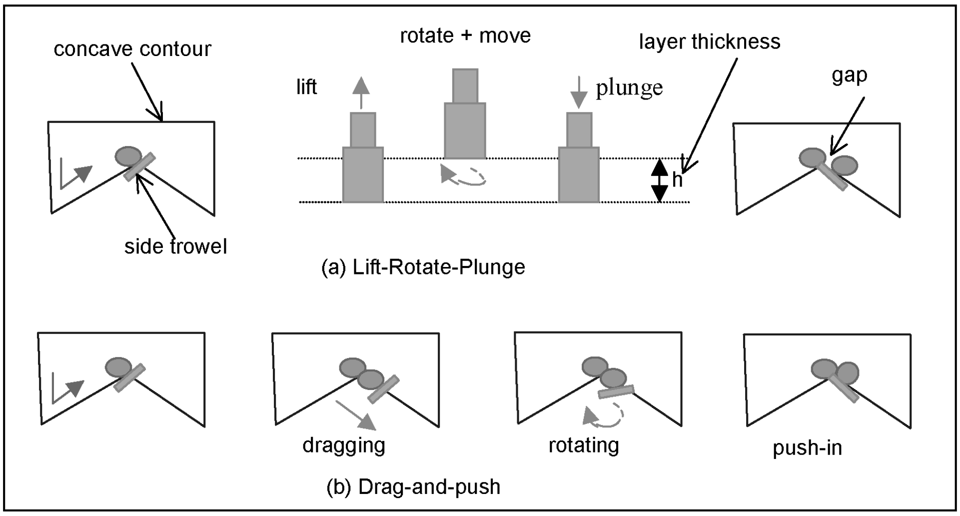


Figure 15 Trowel path planning and nozzle control around sharp convex corners



For concave corners the trowel must change its position as it changes its orientation to avoid colliding with the just extruded material on the adjacent edge. However, a simple trowel displacement creates a gap at the beginning of the opposite edge, see Figure 16(a).

Figure 16 Trowel path planning and nozzle control around concave corners

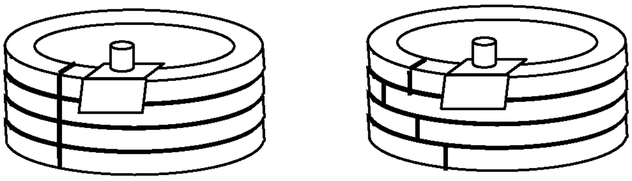


The solution is to use a *drag-and-push* method by

- moving the nozzle while extruding along the direction of the opposite edge and without changing the orientation of the trowel
- once the trowel has cleared the corner pause the nozzle flow, rotate the trowel to be tangent to opposite edge and continue, see Figure 16(b) (Yeh, 2005).

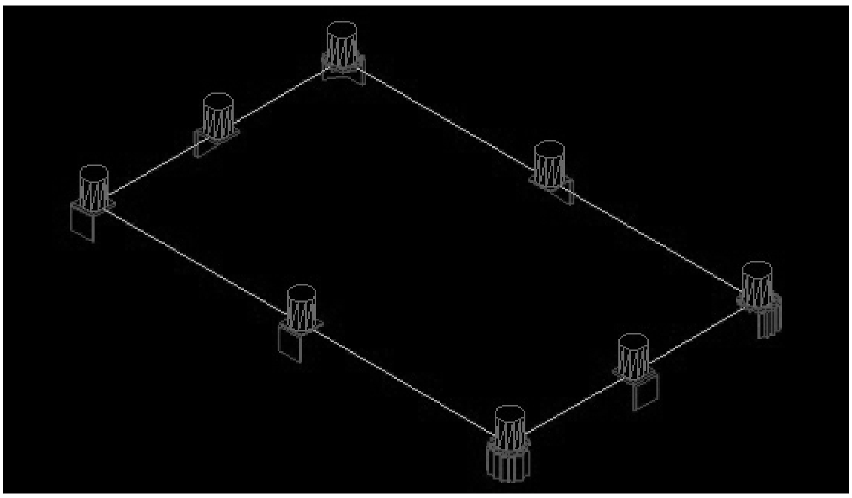
Reasoning about joints and intersections. The bonds formed between the newly extruded and previously extruded material may be weaker, because the older material may already be dry. This typically happens at termination points (e.g., at intersections and at completion points of loops). If these terminations line up vertically across layers, then extended cracks may develop. The solution is to try to stagger the terminations points, see Figure 17.

Figure 17 Non-staggered vs. staggered starting points. Staggered starting points prevent crack propagation



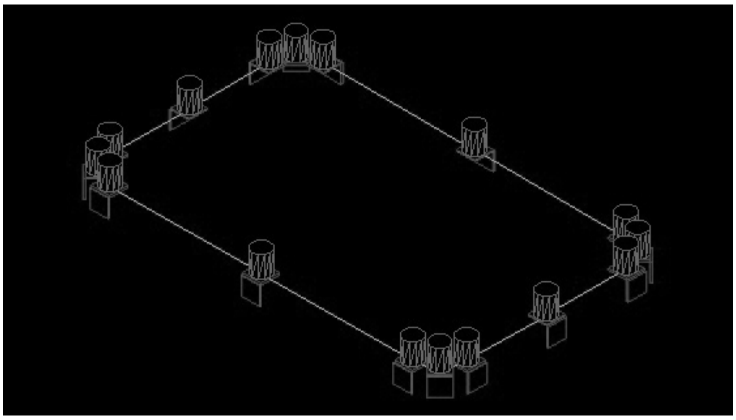
Path planning. Path planning problems in the sense of minimum graph edge traversals has been extensively studied in rapid prototyping (Park, 2003; Park and Choi, 2000; Persson, 1978) and in graph algorithms like the mixed Chinese Postman problem (Edmonds and Johnson, 1973; Raghavachari and Veerasamy, 1998); research results for these areas can be leveraged. With respect to MSF the layer task graph defines a series of layering graphs, where each layer graph defines a minimum graph traversal problem. The layering graph may contain both undirected and directed edges which makes the problem NP-hard. Adjacent layering graphs tend to be similar, so the solution from one layer maybe reused. Also, the physical thickness of the layers can be adjusted to increase or decrease drying time to compensate for the amount of time needed to perform a full traversal. Figure 18 illustrates some initial trowel path planning results on various sample contours for a single-orifice, single-trowel MSF nozzle.

Figure 18 Trowel path. From the top right corner in clockwise order: (a) rectangular contour; (b) rounded corner rectangular contour; (c) NURBS contour and (d) contour with concave arch

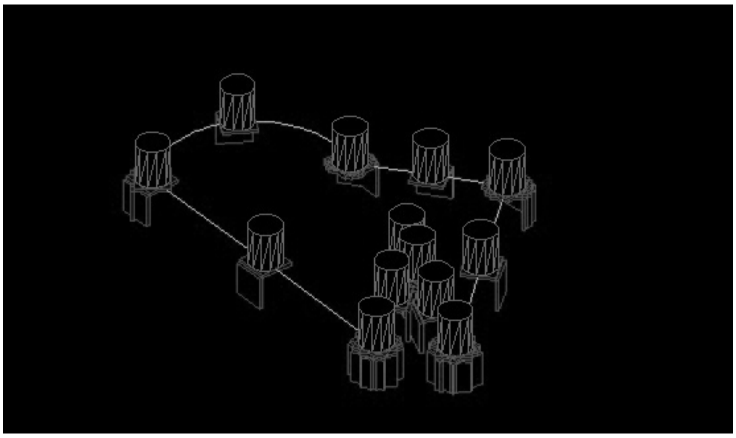


(a)

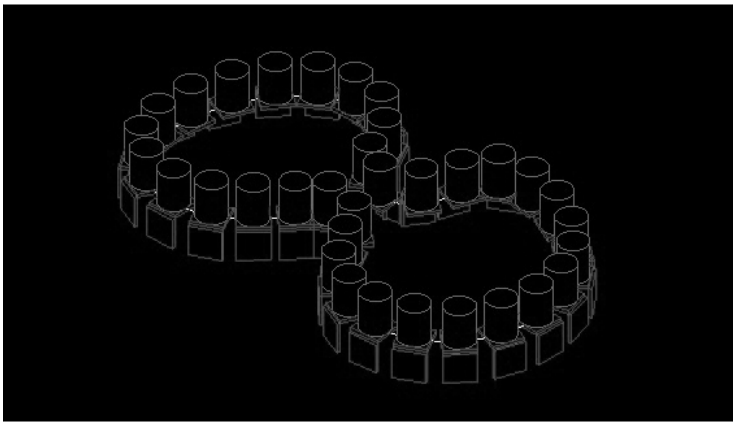
Figure 18 Trowel path. From the top right corner in clockwise order: (a) rectangular contour; (b) rounded corner rectangular contour; (c) NURBS contour and (d) contour with concave arch (continued)



(b)



(c)



(d)

4.6 Logistics issues

The new construction paradigm introduced by the Contour Crafting technology would necessitate a breakthrough approach to construction logistics. A technology that can build a house in one day requires a support logistics to procure and make available all the needed materials at the correct site in correct time sequence. A sophisticated and computerised system of bill of materials, order dispatching, transportation, and dynamic site layout planning will be needed. In addition, an infrastructure network with various warehouse nodes with rapid kitting and loading capability must be implemented. The new technology will bring numerous logistics and optimisation (from high level planning to detailed nozzle path panning and utilities module assembly planning) research possibilities to the industrial engineering profession.

5 Conclusion

Contour Crafting is the only layered fabrication technology which is suitable for large scale fabrication. CC is also capable of using a variety of materials with large aggregates and additives such as reinforcement fibre. Due to its speed and its ability to use in-situ materials, Contour Crafting has the potential for immediate application in low income housing and emergency shelter construction. One of the ultimate goals of humans is building habitats on other planets for long term occupancy. The CC approach has direct application to extraterrestrial construction. A current NASA supported project aims at studying the applicability of CC for Lunar construction (Khoshnevis et al., 2005).

There are numerous research tasks that need to be undertaken to bring the CC construction technology to commercial use. The activities reported in this paper are the first few steps toward realisation of actual full scale construction by Contour Crafting. Readers may obtain updated information on research progress and view video clips and animations of construction by CC at www.ContourCrafting.org.

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References

Edmonds, J. and Johnson, E.L. (1973) 'Matching, Euler tours and the Chinese postman', *Mathematical Programming*, Vol. 5, pp.88–124.

Hwang, D. (2005) *Experimental Study of Full-Scale Wall Construction using Contour Crafting*, PhD Dissertation, Industrial and Systems Engineering, University of Southern California, May, Los Angeles, CA 90089, USA.

John, G.E. and Hiroshi, S. (1996) 'Construction automation: demands and satisfiers in the United States and Japan', *Journal of construction Engineering and Management*, Vol. 122, pp.147–151.

Khoshnevis, B. (1998) 'Innovative rapid prototyping process making large sized, smooth surface complex shapes in a wide variety of materials', *Materials Technology*, Vol. 13, pp.52–63.

Khoshnevis, B. (2004) 'Automated construction by contour crafting-related robotics and information technologies', *Automation in Construction*, Vol. 13, pp.5–19.

Khoshnevis, B.M., Bodiford, P., Burks, K.H., Ethridge, E., Tucker, D., Kim, W., Toutanji, H. and Fiske, M.R. (2005) *Lunar Contour Crafting – A Novel Technique for ISRU Based Habitat Development*, American Institute of Aeronautics and Astronautics Conference, Reno, January.

Kwon, H. (2002) *Experimental and Analysis of Contour Crafting (CC) Process using Uncured Ceramic Materials*, PhD Dissertation, Industrial and Systems Engineering, University of Southern California, August, Los Angeles, CA 90089, USA.

Park, S.C. (2003) 'Tool-path generation for Z-constant contour machining', *Computer-Aided Design*, Vol. 35, No. 1, pp.27–36.

Park, S.C. and Choi, B.K. (2000) 'Tool-path planning for direction-parallel area milling', *Computer-Aided Design*, Vol. 32, No. 1, pp.17–25.

Persson, H. (1978) 'NC machining of arbitrarily shaped pockets', *Computer-Aided Design*, Vol. 10, No. 3, pp.169–174.

Raghavachari, B. and Veerasamy, J. (1998) 'Approximation algorithms for the mixed Chinese postman problem', in Bixby, R.E., Boyd, E.A. and Rios-Mercado, R.Z. (Eds.): *Integer Programming and Combinatorial Optimization, 6th International IPCO Conference, Houston, Texas*, *Lecture Notes in Computer Science*, Springer, June, Vol. 1412, pp.169–179.

Yao, K-T. and Gelsey, A. (1994) 'Intelligent automated grid generation for numerical simulation', *Proceedings of the Twelfth National Conference on Artificial Intelligence*, pp.1224–1230.

Yao, K-T. and Gelsey, A. (1996) 'Intelligent automated grid generation for numerical simulation', *AI for Engineering Design Analysis and Manufacturing*, Vol. 10, No. 3, pp.215–234.

Yeh, Z. (2005) *Trowel Path Planning for Contour Crafting*, PhD Dissertation, Industrial and Systems Engineering, University of Southern California, December, Los Angeles, CA 90089,USA.