적층조형설비(CC)을 이용한 3차원모형 제작에 대한 연구

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Initial investigation of 3D free form fabrication Using Contour Crafting with the pivoting side trowel

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ABSTRACT

The Contour Crafting (CC) process, which has been developed at the University of Southern California, aims at automated construction of whole houses as well as sub-components. For this purpose, new trowel mechanism is basically needed in order to fabricate the true 3D shape. This paper presents our concepts and initial investigation of 3D free form fabrication using the pivoting side trowel. Specifically, the status of research and development of the processand experiments with ceramics materials, and its potential application areas are detailed.
Keywords: Contour Crafting, Trowels, Automated Construction.

1. Introduction

Contour Crafting (CC), an additive fabrication technology that uses computer control to exploit the superior surface-forming capability of troweling to create smooth and accurate planar and free-form surfaces (Khoshnevis *et al.*, 2001; Khoshnevis, 1998), is a patented fabrication process. Using the layering approach afforded by troweling,an ancient process, a wide range of surface shapes may be created with fewer types of troweling tools than are needed for traditional plaster handwork and sculpting. Some of the important advantages of the patented Contour Crafting method compared with other rapid prototyping processes are better surface quality, higher fabrication speed, and a wider choice of materials.

A common limitation associated with most current layered fabrication methods is the maximum size of the component that can be fabricated,generally not larger than a meter in any dimension. With Contour Crafting, components as large as multi-story buildings can be made at relatively high speed with a variety of materials.

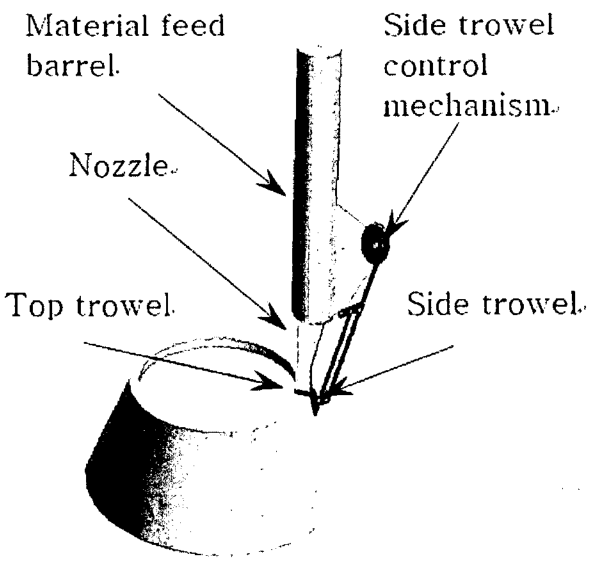

Figure 1. Contour Crafting Process

In CC, computer control is used to take advantage of the superior surface forming capability of troweling to create smooth and accurate, planar and free-form surfaces (Landfoam FAQ, 2000). The layering approach enables the creation of various surface shapes using fewer different troweling tools than in traditional plaster handwork and sculpting. It is a hybrid method that combines an extrusion process for forming the object surfaces and a filling process (pouring or injection) to build the object core. As shown in Figure 1, the extrusion nozzle has a top and a side trowel. As the material is extruded, the traversal of the trowels creates smooth outer and top surfaces on the layer. The side trowel can be deflected to create non-orthogonal surfaces. The extrusion process builds only the outside edges (rims) of each layer of the object. After complete extrusion of each closed section of a given layer, if needed filler material such as concrete can be poured to fill the area defined by the extruded rims.

2. Description of CC machine

CC machine consists of a flat rotary worktable and a vertical extrusion head capable of linear motion along three coordinate axes. In addition, the machine comprises an extrusion system as well as five stepper motors. The extrusion system consists of a top and side trowel, a cylinder that contains the raw material, and a piston and a threaded feed rod which extrudes the raw material through a nozzle.

The process utilizes a Programmable Multi-Axis Controller (PMAC), a high-performance servo motion controller, capable of controlling up to eight axes of motion (Delta Tau Data Systems, 1996 a, b). The eight axes can be all synchronized for completely coordinated motion; each axis can be put into its own coordinate system for eight completely independent operations; any intermediate arrangement of axes into coordinate systems is also possible. Limit switches are used to restrict motion to specified limits.

The machine shown in Figure 2is modified to fabricate the complex geometrical parts for the CC process of uncured ceramic materials, which include the convex, concave, and sharp corner shapes. The machine consists of a trowel rotation system, and a vertical extrusion head capable of linear motion along three coordinate axes.

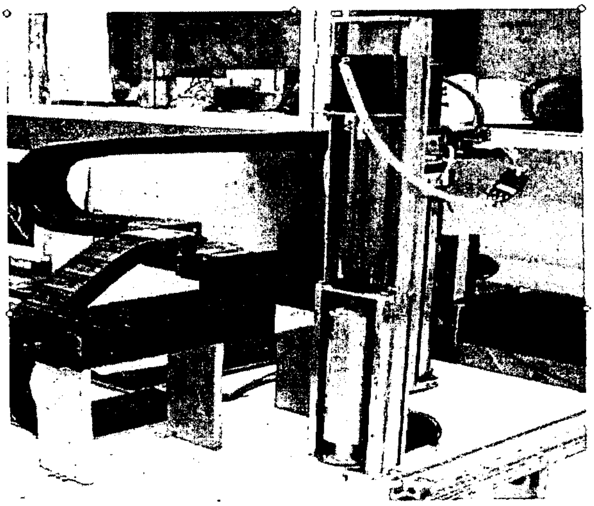

Figure 2. CC machine for fabricating the complex geometrical part

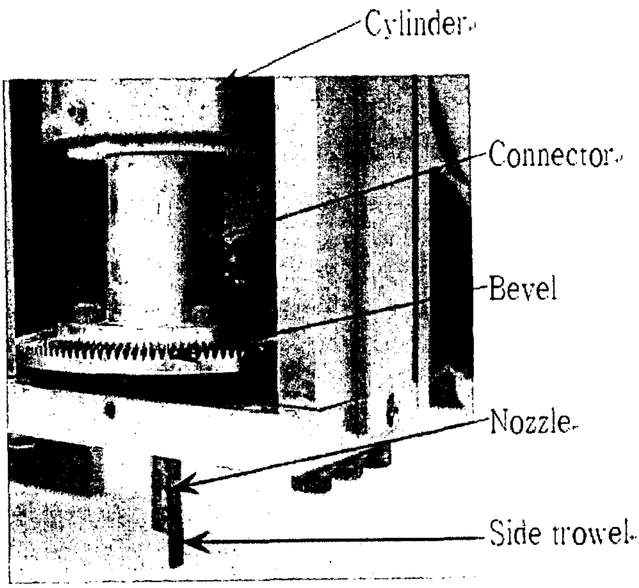

Figure 3. Trowel rotation system of CC process

The trowel rotation mechanism shown in Figure 3consists of a bevel gear, and a connector. The ratio of the bevel gear is 4 to 1, and is derived by the

5^{th}stepper motor. The connection mechanism allows the raw material to flow continuously from the cylinder to nozzle, and can rotate the extrusion system without disturbing the material flow while fabricating complex curves.
In order to enhance the capability of CC for building certain primitive geometries and hybrid geometries made of these primitives, a nozzle with movable side trowel is designed and assembled into the existing machine as depicted in Figure 4. This nozzle assembly will provide for intricate trowel motions to create various desired geometries.

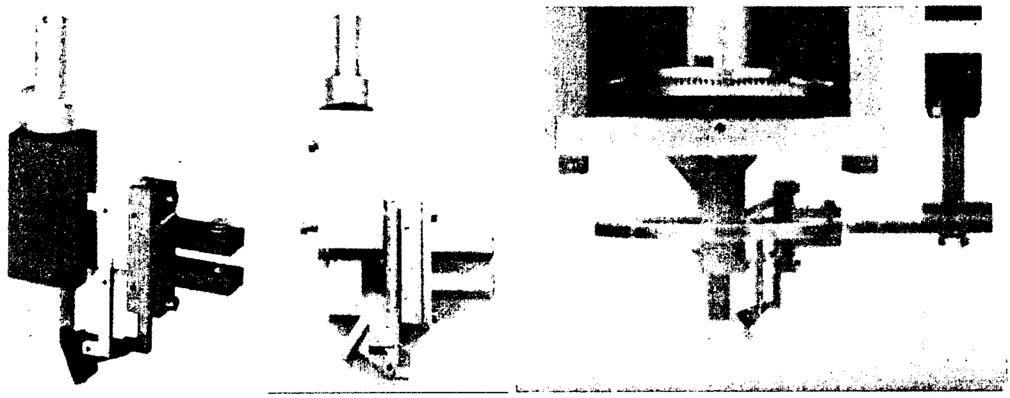

Figure 4. Design and two views of the movable nozzle assembly

3. Preliminary result

3.1 Fabrication of 2.5D shapes

The machine shown in Figure 2 is modified to fabricate the complex geometrical part for the CC process. Simultaneously, experimental investigations are conducted to find preliminary side trowel effects. Several experiments were performed with uncured ceramic materials to fabricate diverse geometrical parts that include the convex, concave, and sharp corner shape. When fabricating complex parts, the experiments demonstrated that the original two-trowel system has several limitations:

• As shown in Figure 5, it is unable to fabricate the smooth surface of a square part that has a sharp corner because the backside of the side trowel drags the wall of the part when the sharp corner is being fabricated. The magnitude of the dragging effect is magnified when the radius of the square corner is smaller. When the clay contains more water, also, its magnitude is increased because the level of viscosity is decreased in the liquid state, and makes the clay stickier.

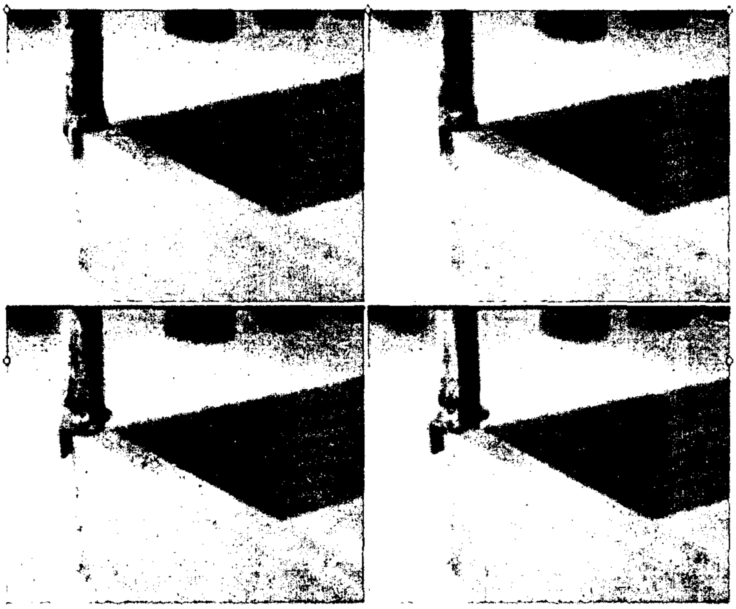

Figure 5. Sequence of the process showing the effect of the long side trowel when fabricating sharp square corners.

Figure 6. Sequence of the process showing the effect of the long side trowel in fabricating concave corners.

• As shown in Figure 6, it is unable to fabricate the smooth surface of other complex parts that have a concave corner because the backside of the side trowel pushes inward the wall of the part when the concave corner is being fabricated. Also, the front of the side trowel cuts the wall surface of the part when the end of the concave corner is being fabricated. The magnitude of these effects is amplified when the radius of the concave corner is smaller. When the clay contains more water, also, the clay part would sag or collapse outward because the clay is transformed into the liquid state.

To overcome these limitations, several other types of trowels were tested with uncured ceramic materials. One of the best side trowels shown in Figure 7 has several advantages in addition to being able to fabricate diverse geometrical parts that include convex, concave, and sharp corner shapes.

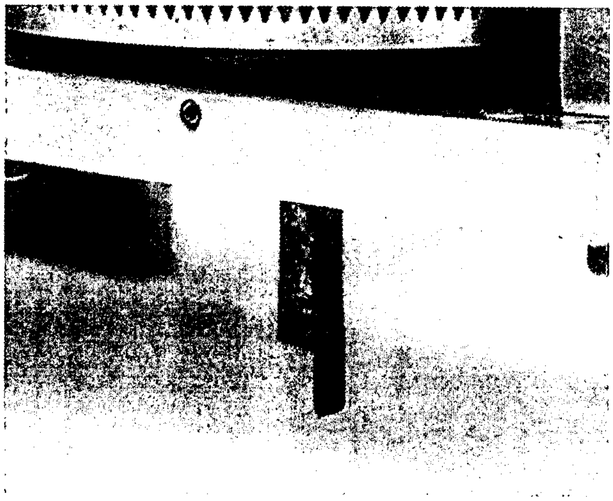

Figure 7. Short side trowel without the top trowel

• As shown in Figure 8, it is able to fabricate the smooth surface of a square part that has a sharp corner because the backside of the side trowel is absent. The wall of the part cannot be dragged by the side trowel anymore when the sharp corner is being fabricated. The dragging effect is completely removed until the radius of the square corner is reduced below 2.5 mm.

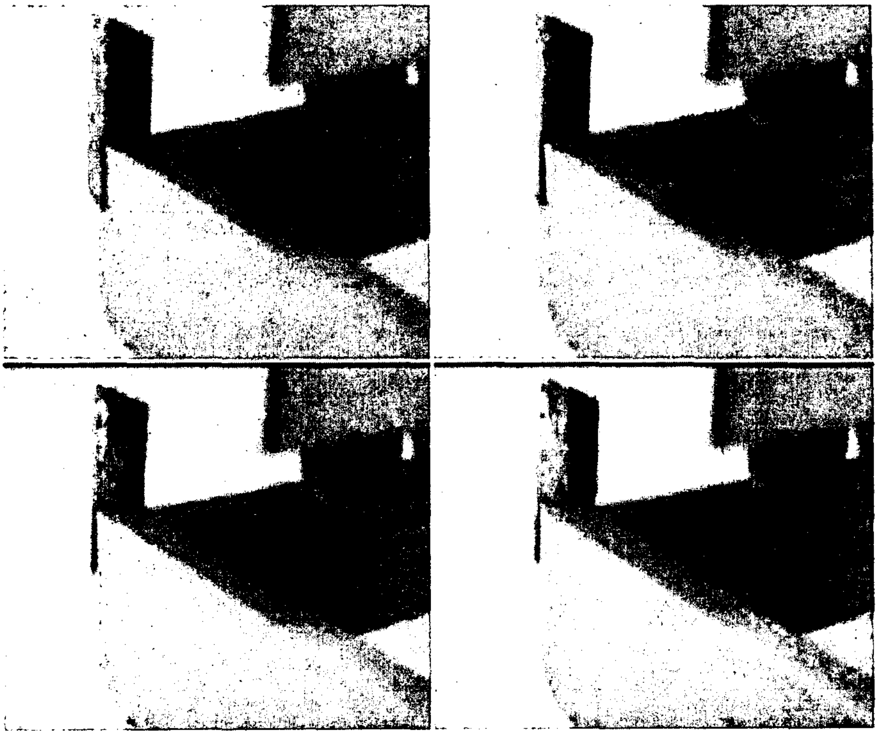

Figure 9. Sequence of the process showing the effect of short side trowel in fabricating sharp square corners

• As shown in Figure 9, the smooth surface of other complex part that has a concave corner can be fabricated with the short side trowel because the backside of the side trowel is removed. When the concave corner is being fabricated, the wall of the part cannot be pushed inward anymore because the length of the side trowel (5 mm) is the same as that of orifice. Also, the wall surface of the part cannot be cut by the front side of the side trowel when the end of the concave corner is being fabricated. However, these effects might occur when the radius of the concave corner is smaller than the length of the side trowel (5 mm).

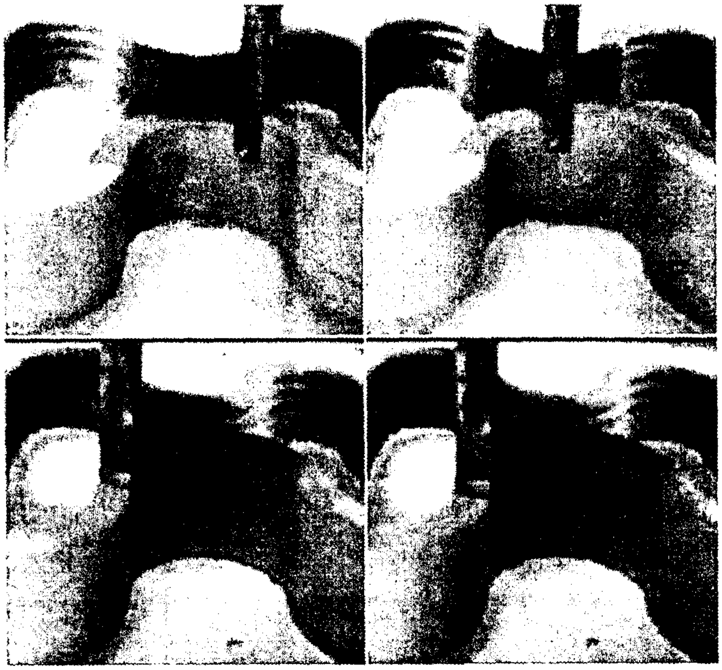

Figure [illegible]. Sequence of the process showing the effect of the [illegible] in fabricating concave corners

Building on the above detailed experimentation scheme and results, significant progress has been made towards realizing a variety of 2.5D shapes using CC, as shown in Figures 10. These complicated profiles were created through the rotation of the nozzle about a vertical axis, while keeping the rotary table stationary. As shown in Figures 17 and 18, we have currently optimized the process mechanism to produce complex geometric parts such as the square, convex, and concave geometry. These efforts would ultimately give the capability to fabricate a true 3D part. Also, a significant progress has been made towards realizing a variety of 2.5D and 3D shapes with vertical walls using CC, as shown in Figures 18 and 23. These complicated profiles were created through the rotation of the nozzle about a vertical axis, while keeping the rotary table stationary. In the following subsection, the process algorithm, and the challenges and improvements of fabricating 3D parts are detailed.

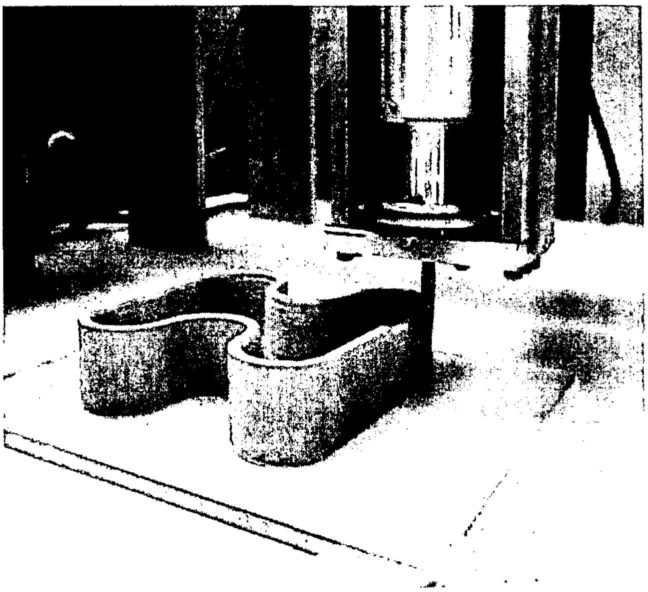

Figure 10. Contour Crafting of 2.5D parts.

3.2 Fabrication of 3D shapes with the pivoting trowel

Adapting the movable side trowel control mechanism shown on Figure 4, our existing CC fabrication machine is modified shown on figure 11 (a) for building certain primitive geometries and hybrid geometries made of these primitives. The primitives will be carefully chosen so that these form the basic shapes for the scaled models of adobe houses. As shown in Figure 11 (b), typical primitives that we have considered thus far are flat floors, straight walls, arches, vaults, and domes. Hybrid geometries, formed as a direct combination of these primitives, will represent scaled models of adobe houses such as those adopted by CalEarth. Figure 12 shows one such housing structure.

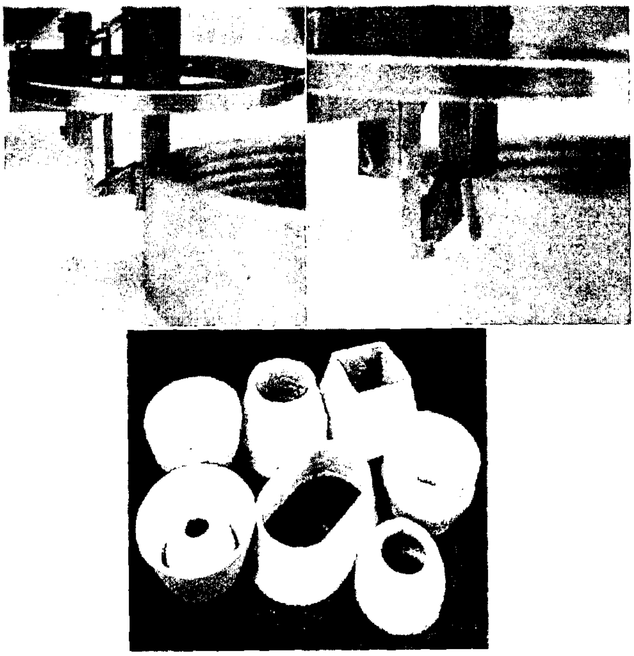

Figure 11. CC process with the movable side trowel. (a) Actual process, and (b) various primitive geometries fabricated with the movable side trowel.

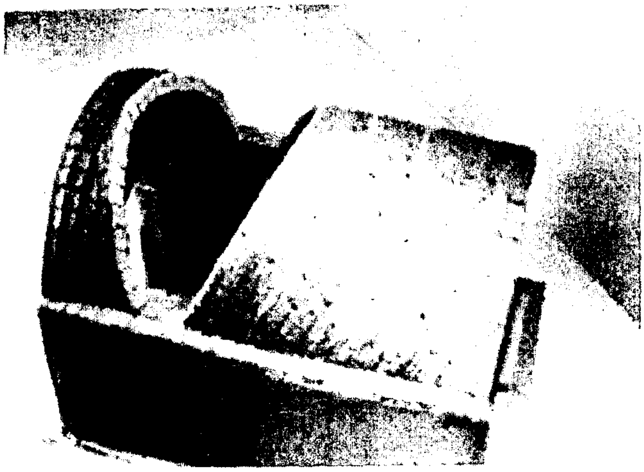

Figure 12. A vault structure made of clay bricks (Source: Khalili, 2000).

We will also investigate co-extrusion of multiple materials using a combination of nozzles. This feature will build on our recent results in producing sections with cavities by forcing the material through a nozzle with a central mandrel. Here, various materials may be co-extruded if the mandrel itself is hollow and works as a nozzle to deliver a second material. This feature will provide the capability to lay base material as well as certain reinforcements simultaneously. We may use additional mandrels for creating hollow cavities inside the depositions. Furthermore, for constructing walled structures, we will first construct rims using the nozzle system, and will fill the intervening space between wall-rimsusing a bulk-filling mechanism.

4. Summary

Preliminary investigation of CC process indicates that the process is feasible and has significant potential in construction automation approach of large objects. The process aims at automated construction of whole houses as well as sub-components. The potential of CC became evident from the initial investigations and experiments with various materials and geometries. Using this process, a single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run.

Experiments with ceramics material show the versatility of the process relative to the use of a variety of fabrication materials. In addition to the use in rapid fabrication of large components, the process also has its niche in rapidly fabricating certain components for aerospace and automotive industries, where minimization of green machining is warranted.

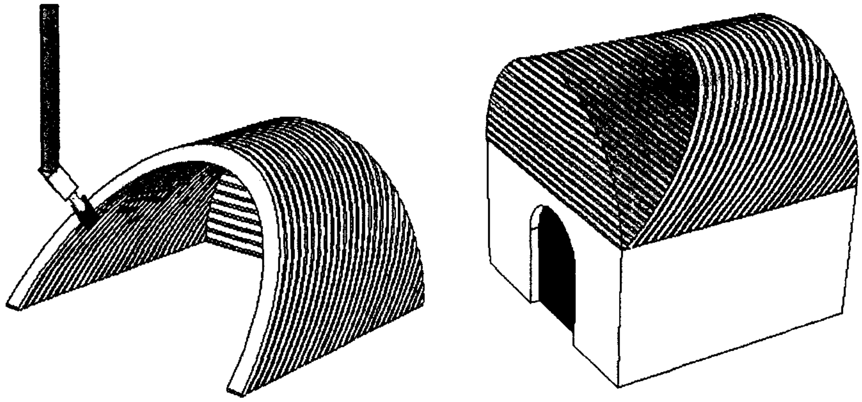

Figure 13. Our approach to fabricate supportless structures

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저자소개

권 홍 규: 동국대학교 산업공학과를 졸업하고 USC(남가주대학) 산업시스템학과에서 공학석사 및 박사학위를 취득하였으며, 현재 충주대학교 산업경영공학과 겸임교수로 재직중임. 주요과심 분야는 CIM, FMS, Robotics, 생산자동화, Simulation