CONTOUR CRAFTING – STATE OF DEVELOPMENT

Behrokh Khoshnevis, Professor
Industrial & Systems Engineering
University of Southern California
Los Angeles, CA 90089-0193
Khoshnev@usc.edu

Contour Crafting, 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, is under development at the University of Southern California (USC). 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.

Surface finish is a key issue that must be addressed in most rapid prototyping processes. The surface of the component is often rough because the component is created layer-by-layer, and in some techniques the layers are generated point-by-point. This roughness generally has a wavelength and amplitude that are proportional to the layer thickness. The approaches commonly employed to reduce the roughness include reducing the layer thickness and/or using post-fabrication grinding. Modifications to existing processes that improve the surface finish would be desirable for reducing fabrication time and cost.

A second limitation associated with most current rapid prototyping methods is the maximum size of the component that can be fabricated, which is generally not larger than a meter in any dimension. However, there is a need to fabricate large-scale components of various materials within a cost-effective time frame, particularly in the automotive and aerospace industries. With Contour Crafting components as large as real scale concept car models, can be made at relatively high speed with a variety of materials.

The key feature of Contour Crafting is the use of two trowels, which in effect act as two solid planar surfaces, to create surfaces on the object being fabricated that are exceptionally smooth and accurate. Artists and craftsmen have effectively used simple tools such as trowels, blades, sculpturing knives, and putty knives, shown in Figure 1, with one or two planar surfaces for forming materials in paste form since ancient times. Their versatility and effectiveness for fabricating complex free-form as well as

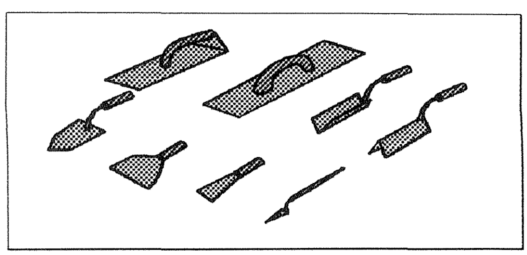

Figure 1. Traditional surface-forming tool

splanar surfaces is evidenced by ancient ceramic containers and sculptures with intricate or complex surface geometries as well as detailed plaster work that have shapes as complicated as flowers, on the walls of rooms. Surface shaping knives are used today for industrial model making (e.g., for building clay models of car bodies). However, despite the progress in process mechanization with computer numerical control and robotics, the method of using these simple but powerful tools is still manual, and their use in manufacturing is limited to model building.

In Contour Crafting, 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. 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 2, the extrusion nozzle has a top and a side trowel. As the material is extruded, the travel 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 can be poured (liquid monomers, for example) or injected (material in paste form, such as thermosets, ceramic or metal powders, cements,) to fill the area defined by the extruded rims.

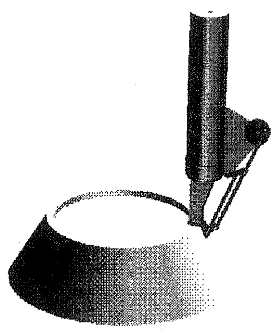

Figure 2. The extrusion assembly with top and side trowels

Some internal walls can be extruded within each layer to create square hatches or other types of hatches (see Figure 3). The hatching process may be required for large objects, since curing can start before the filler material gets a chance to spread over the entire surface of the layer. However, when hatching is used each of the small hatches is filled separately, which because of their small size allows more control over the spreading and curing of the filler material. Hatching can also accelerate the forming process because it provides for concurrent extrusion and filling (i.e., as the extrusion nozzle creates new hatches, previously made hatches can be filled). The computer positions the pouring outlet (or the injection mechanism) so that the liquid material is spread evenly within the enclosed layer. To control the amount of filler to be poured or injected, various types of sensors

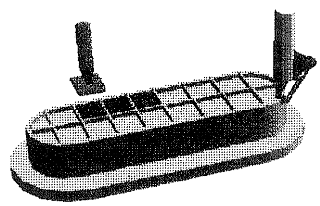

Figure 3. Internal hatches filled by pouring or injection

can be used.

One important characteristic of the special extrusion process used in this method is that the rim surface that faces the interior of the object does not require a smooth surface because it will be covered and bonded with the filler material. Therefore, despite unavoidable variations in the rate of extrusion, the outer and top sides of the extruded rim will be sharply defined and accurately controlled by the trowels, while excess material will be accommodated on the inner flank. Because of the intrinsic tolerance of this process simpler and less costly extrusion mechanisms can be used compared with those required in current fused deposition machines.

Configurations of the trowel assembly have been designed that can make top surfaces (and internal walls) and oblique surfaces with opposing slopes, that can fabricate overhangs and undercuts, as shown in Figure 4. Other designed variations can create doubly curved (e.g., spherical) surfaces.

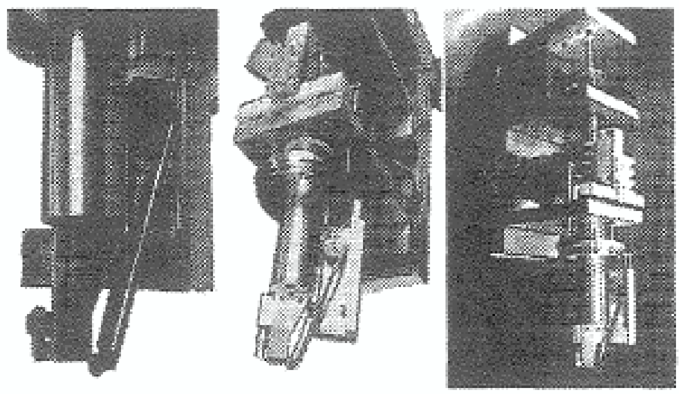

Figure 4. Various views of the prototype nozzle

Some advantages of Contour Crafting compared with existing rapid prototyping methods are:

- Exceptionally smooth and accurate surfaces are created because of the elimination of surface discontinuities.
- Fabrication of a part is considerably faster because the layer thickness is typically much larger than layer thickness in other rapid prototyping processes.
- A wide variety of materials can be used, including thermosets, thermoplastics, metal and ceramic pastes mixed with a binder, and also materials that are not commonly used in rapid prototyping such as plaster, cement, clay, and concrete.
- Better structural properties afforded by the large size of the nozzle orifice which allows the addition of filler materials such as loose or continuous fiber.
- Prototypes and final parts much larger than 1 to 2 meters can be fabricated such as parts for airplane, automotive, marine, and building construction components (e.g., doors and windows) using large gantry-type robots for nozzle movement.
- Smooth internal surfaces of casting molds can be rapidly fabricated using the process.

Contour Crafting has certain limitations arising from the use of the side trowel. For example, very small hollow volumes, such as small holes, can't be made because they cannot accommodate the side trowel. Also it is not possible to use the side trowel to create features that are relatively thin (e.g., a vertical blade). In such cases, the extrusion deposition thickness may exceed the feature thickness. The extent of this limitation, however, depends on the size of the side trowel, which could be 3 mm x 3 mm for fabricating small objects and 2 cm x 2 cm for large objects.

The principle feature of the Contour Crafting process is the use of a simple tool, i.e., trowel. However, despite the apparent simplicity of its principle, there are major challenges that must be overcome to successfully implement the concept. Two especially noteworthy challenges are: a) complicated shrinkage patterns due to balk deposition of various materials, and b) complications in generation of tool (i.e., nozzle assembly) path, especially for sharp corners.

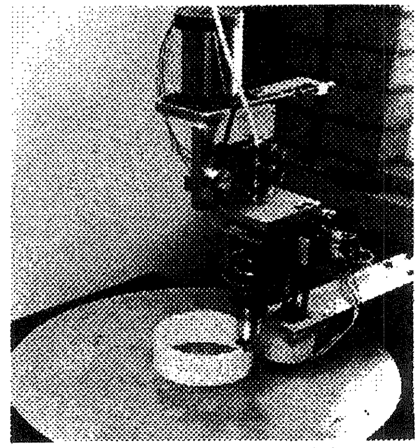
Figure 5. Machine 1 used for thermoplastics fabrication

Experiments with Thermoplastics:

To date, we have constructed two Contour Crafting fabricators that can produce simple parts such as cylinders, cones, and planar surfaces using polystyrene. The extrusion system in these fabricators consists of a temperature-controlled nozzle and barrel assembly through which thermoplastic material, in the form of filament coils 3 mm in diameter, is fed via a system of gears and rollers. The first machine (Figure 5) has no environment control, while the second one (Figure 6) has a closed chamber the temperature of which can be controlled. With these machines we have built polystyrene parts that have a surface quality of 2.4 microns (96 micro inches). Note that for high quality die cast parts this figure is generally 3.1micron (125 micro inches). The layers used to build the polystyrene parts were ranged from 1 mm to 5 mm thick. Figure 7 shows various rotational parts made by the process using polystyrene. Larger parts in this figure are 25 cm in height and each part is built in less than 20 minutes. A third machine for making more complicated shapes is under construction. The second machine was used extensively to study the impact of various process parameters such as trowel angle, extrusion rate, nozzle travel speed, layer thickness, cooling rate, etc. The informative results of these experiments are compiled in a Ph.D. dissertation [Russell, 1999].

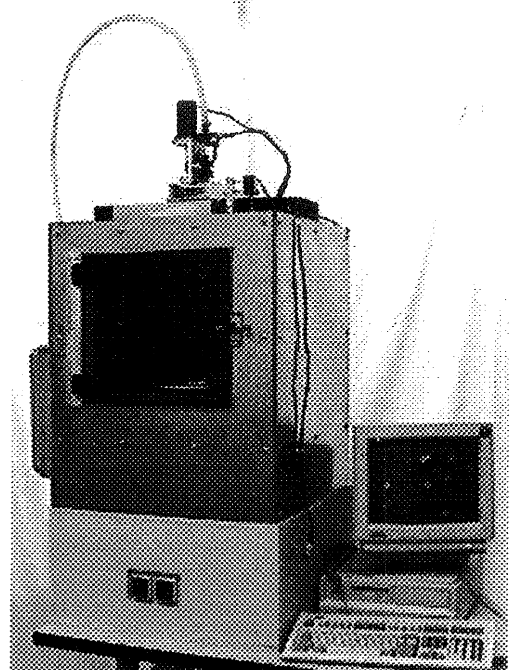
Figure 6. An environment controlled CC machine.

Experiments with Ceramics:

We have applied the CC process to uncured ceramics such as plaster and clay-like materials, with specific focus on achieving a high surface-finish with a minimum processing time, with the highest geometric accuracy. The machine shown in Figure 8 is customized for the CC processing of uncured ceramic materials such as spackling compound and clay models. The machine consists of a flat rotary worktable and a vertical extrusion system capable of rotary motion along its vertical axis and linear motion along three coordinate axes (i.e., a 4 axis machine).

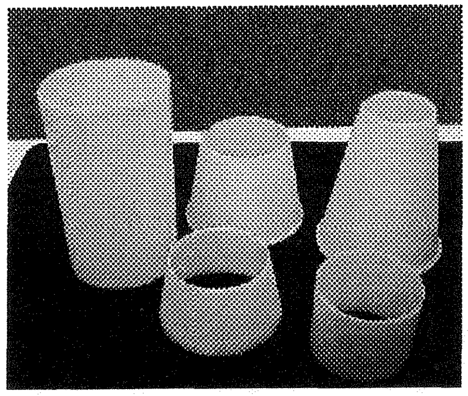

Figure 7. Some experimental rotational parts made out of polystyrene

An off the shelf spackling compound made by Custom Building Products, Inc. was used. It had the advantages of being commercially available, inexpensive, light in weight, and having quick setting time. The paste contains Acrylic Copolymer, Amorphous Silicate, 3% water per unit volume of material, and small spherical hollow glass fillers. The paste models have a complete setting time of approximately three hours after being exposed to air.

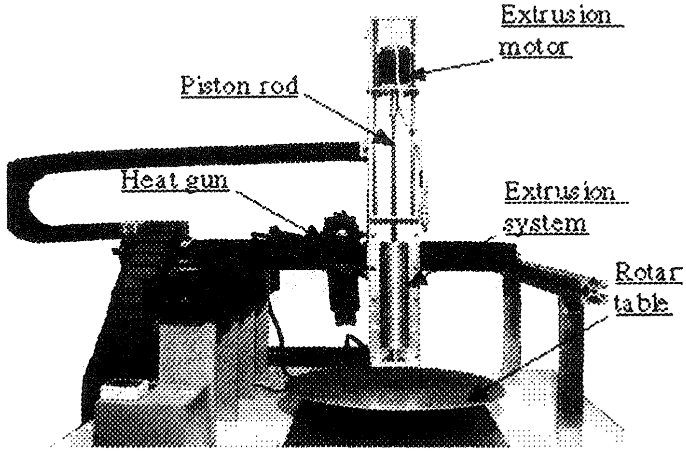

Figure 8. CC machine for ceramic part fabrication

The clay used in our experiments was procured from America Ware, Inc. in Los Angeles. The clay contained: Pioneer Tak 2882, Taylor Ball clay, Barium Carbonate, Soda Ash, Sodium Silicate, and 35% water per unit mass. The clay models were produced at room temperature and then bisque-fired in a kiln at 1063^{0}C - 1066^{0}C for 10 hours. For glazing, a second firing at 1003^{0}C was carried out for eight-nine hours.

Both the clay and paste models showed improved compressive strength qualities after compression through the extrusion system. This enabled the lower layers made of these two materials to maintain their shape and dimension even as additional deposited on them. As can be seen in Fig. 10 and 11, the layers directly below the point at which material was being deposited, compressed vertically and expanded horizontally but returned to their original form (spring-back) once the pressure was released. We believe that if the homogeneity of the material in the cylinder can be maintained, these effects would be consistent through every section of each layer, thus giving the model superior mechanical properties as compared to die casting methods of manufacturing.

Our current research efforts are focused on improving the process technology using spackling compound and clay, especially with regard to gaining physical and experimental understanding of the influence of the various identified design parameters on the product quality. Furthermore, we are investigating the compressibility of clay, as well as the adaptability of the process mechanism to produce parts of different shapes. We are also working on a method of filling the extrusion cylinder, by which air pores contained in the raw material could be excluded simultaneously. A better surface finish and structural strength is expected to result from these endeavors.

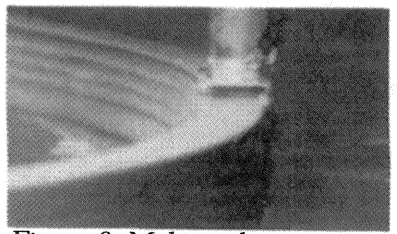

Figure 9. Making clay parts with 3 mm layers

The pressure between the trowel and the upper layer of the model is a core factor affecting the surface quality of the CC process. Hence, we are thoroughly studying the correlation between pressure, and linear speed and extrusion rate with a finite element analysis method. We have also started creating non-rotational parts and refining our algorithms for creation of sharp corners. As the process is improved and refined, it is anticipated that composite as well as metal and ceramic parts will be fabricated. Blending the reinforcement phase with the powder particles prior to extrusion and deposition could make composite parts with particulate or short fiber reinforcements.

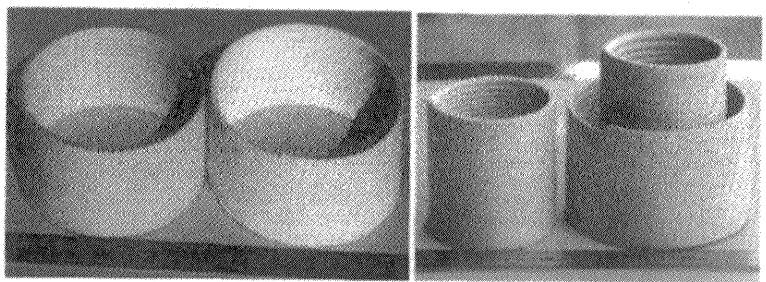

Figure 10. Parts made with spackling paste and clay

Software Development:

Unlike existing layering techniques, which assume uniform layer thickness and vertical sides for each layer, actual slopes of the sides of each layer must be considered in Contour Crafting. Therefore, an interface with solid modeling is required that involves approximating the surface with a series of horizontal slices that are not simply extrusions of a contour. This is because the apparatus has a trowel with variable orientation that can also be shaped for a better fit to the surface. This operation is more like 5-axis machining than the usual slicing for rapid prototyping, consequently, rather than working with an STL file, which is a polygonal approximation, Contour Crafting has to work directly from an exact solid model.

The path generated by moving the trowel to create a given surface is called trowel-path, which is different from conventional NC cutter-path. There are two major differences between the two paths: 1) cutter-path is based on cutting while trowel-path is based on press-forming, and 2) NC cutters are usually cylindrical while trowels are planar. Because of these differences, trowel-path generation should be based on new concepts. totally new concept. Ultimately we should generate trowel-paths for 3D parts. Since parts are made layer by layer in CC, the 3D model of parts have to be sliced. Slicing is not a trivial in CC because of peaks and flat areas [Dolenc, 1994]. Again, unlike in other RP methods, slicing in CC has to incorporate an accessibility analysis, and hence it is a complicated procedure. We have approached this part of our research in two phases. First we have considered only 2.5D parts (i.e., sweeping models). Note that he profiles of several layers cut from each segment of a 2.5D model remain identical. Experiment on 2.5D will lay a foundation for dealing with other 3D cases, which we have started studying.

We classify the 2.5D model into three categories: polygon, composite curve (lines and arcs are mixed) and parametric curves such as B-Spline or NURBS. If any of these shapes is convex, then the trowel can access the entire surface and the trowel paths can be generated easily. In most cases, however, these curves are not convex. How to access the concave corner becomes an interesting challenge. We have developed a software system that deals with the above shapes. Convexity has to be determined in the beginning. For the polygon, we use the cross product of the forward and the backward vectors on each vertex to determine its convexity. Composite curves can be processed in the same way as polygons, however, they are always concave except in the tangential connection case. Determining the convexity of a parametric curve is different. In this case the whole curve is recursively sub-divided into small segments, then the cross product of consecutive normal vectors are used to determine the convexity of the curve.

After the shape is determined as concave, a special algorithm called tail-wiping is used to make the concave corner. The concept is that the trowel may go off the edge and the nozzle extrudes material outside the shape. But just before the material is solidified, the trowel's tail wipes it into the boundary of the shape. The tail-wiping can also deal with the inward arcs of the composite curve and the inward curve of the parametric curve.

Slicing a true 3D model faces different problems. First, the best direction for slicing has to be determined and the directions that results in more variations in contours must be eliminated. Second, the thickness of each slice has to be adjusted to avoid peak and flat surfaces. Finally, since the peripheral surface may not be parallel to the slicing direction, the appropriate trowel deflection angles have to be determined for each point around the slice. Our preliminary algorithm determining the deflection angle calculates the best-fit normal vector of the peripheral surface. Three normal vectors: top, bottom and middle are averaged to a mean vector. Then a delta of the surface and the best-fit surface is calculated. All features of a given part may be fabricated by CC if delta is within the tolerance of accuracy, otherwise the part may have features too small or tight for side trowel positioning.

We have developed a trowel path generator and an animation module for 2.5D designs using OLE Automation. The input of this path generator is a CAD system (IronCAD). The outputs are the G-code for CC machine and the simulation for visual verification.

The trowel paths are generated successfully from different shapes. We also have a Java version of trowel-path generator, which is more flexible than using a CAD system. We are working on an interface (using VBA) between CAD and our path generator to deal with true 3-D models. The path generator will optimize the slices, will compose 2D paths for each slice while determining trowel deflection angles, presents and animation of the toolpath, and finally generates the G-code for the CC machine.

Acknowledgement:

The research and development activities reported in this paper have been supported by two National Science Foundation grants.

References:

1. A Dolenc and I Makela, "Slicing procedures for layered manufacturing techniques" Computer-Aided Design, Vol. 26, No. 2, Februrary 1994, pp 119-126
2. Debasish Dutta and Prashant Kulkarni, "Improving Surface Quality and Throughput in Layered Manufacturing by Adaptive Slicing," 7th International Rapid Prototyping Conference, San Francisco, 1997, pp 94–101.
3. Andrei S. Novac, Cheol H. Lee, Charles L. Thomas, "Automated Thchnique for Adaptive Slicing in Layered Manufacturing," 7th International Rapid Prototyping Conference, San Francisco, 1997, pp 85–93.
4. Calvert, P."Extrusion Freedom Fabrication of Epoxy Resins," Proceedings of the 1996 NSF Design and Manufacturing Grantees Conference, Albuqurque, New Mexico, January 1996.
5. Crockett, R., O'Kely, J., Calvert, P., Fabes, B. Stuffle, K., Creegan, P, and R. Hoffman, "Predicting the Controlling Resolution and Surface Finish of Ceramic Objects Produced by Sterodeposition Processes," Proceedings of Solid Freeform Fabrication Conference, Austin, Texas, August 1995.
6. Khoshnevis, B. "Innovative rapid prototyping process makes large sized complex shapes in a variety of materials," Material Technology, Vol 13, No. 2, 1988, pp 53-56.
7. Khoshnevis, B. S. Bukkapatnam, H. Kwon, j. Sato "Experimental investigations into Contour Crafting for ceramic materials," Proceedings of NSF Grantees Conference, Long Beach, January 1999.
8. Russell, R. "An experimental approach to analyzing polystyrene melt flow when troweling using the Contour Crafting Process," PhD dissertation, University of Southern California, August 1999.
9. Tunaboylu, B., McKittrick, J., Nellis, W.J., and Nutt, S.R., "Dynamic Compaction of Al_2O_3-ZrO_2 Compositions," *J. Am. Ceram. Soc.* 77 [6] (1994) 1605-12.
10. Yeh, Z., "Trowel Path Generation for Contour Crafting," Research Progress Report, University of Southern California, June, 1999.