

# Creating Thin Objects with Bit-mapped Pictures, Characters, or Textures by FDM Helical 3D Printing

Yasusi Kanada  
Dasyn.com, Japan, yasusi@kanadas.com



## Abstract:

Instead of printing layer by layer, thin 3D objects can be printed in better quality (without seams between layers) by printing helically or spirally by FDM. When printing helically or spirally, the amount of extruded filament can be *modulated* using a bitmap; that is, “zero” in bitmap means “thin” and “one” means “thick” (or vice versa). This process generates a thin object, such as a sphere, pod, or dish, with a bitmapped pictures, characters, or textures. A typical example is a globe, which is printed using a bitmapped world map.

**Keywords:** Computer-Aided Manufacturing (CAM), Additive manufacturing, Fused deposition modeling (FDM), Helical/spiral 3D printing, Bitmap, Texture

## 1. Introduction

Fine concave-convex structures, such as pictures, characters, or textures, are sometimes printed on the surface of a 3D-printed object. In conventional 3D modeling methods, the surface structure of objects to be printed must be specified at the design time. There are two problems in this method. One problem is that it is difficult to create fine structures because the model is sliced without taking into account the structures. The other problem is that the surface structure is often printed as a separate layer, and this layer is sometimes easily unstuck and dropped.

Textures or pictures may be mapped to the surface by using *texture mapping* after designing the shape of the object. However, it is not easy for such a “post-processing” method to map the texture exactly.

It would be better to directly map the surface structure to the printing process. It enables an exact mapping. However, it is difficult because each facet of a conventional 3D-model has no structure; thus, it is not easy to map a pictures and/or characters onto the facets in the printing process. In contrast, the direction-specified modeling and printing methods [1] allow mapping them onto the surface structure of the models.

This paper describes a method for creating thin objects with bit-mapped pictures and/or characters by a 3D printing method using fused deposition modeling (FDM). The base 3D-printing method is called “helical/spiral 3D-printing method” [1]. The rest of this paper is organized as follows. Section 2 describes the base method, i.e., the helical/spiral 3D-printing method. Section 3 describes the selection of picture/character mapping method. Section 4 describes a method for modulating 3D-printed surface. Section 5 shows an implementation and several examples including small globes, and Section 6 concludes this paper.

## 2. Helical/spiral 3D Design and Printing Method

Previous papers [1][2] propose a method for designing and printing direction-specified objects, especially

seamless (with no layer connection) thin objects such as a spirally- or helically-printed cup, vase, dish, or sphere. **Figure 1** outlines the process for direction-specified 3D-printing. This process consists of three major steps, i.e., modeling, tool-path (G-code [4]) generation, and 3D printing, similar to the conventional 3D design and printing process. The first step, i.e., modeling, consists of four sub-steps, but the order and the repetitions depends on cases. A method for the modulation step is proposed in this paper, but other steps are explained in the previous papers.

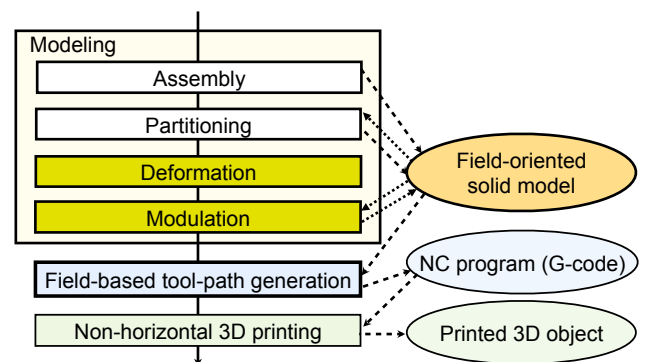


Figure 1: Process for direction-specified 3D-printing

**Figure 2** shows several examples of printed objects using the process described above. The modeling step was programmed in Python and a library called draw3dp.py, which is publicly available at <http://bit.ly/1EBVbSB> (or [http://www.kanadas.com/program/2014/10/3d\\_python.html](http://www.kanadas.com/program/2014/10/3d_python.html)), was used. These objects are designed by deforming the shapes of simple parts such as a helix or a cylinder and assembling them.

These objects are modeled by sequences of strings (straight lines). Each string  $S_i$  can be represented by

$$S_i = (P_{i_{\text{start}}}, P_{i_{\text{end}}}, c_i, v_i)$$

where  $P_{i_{\text{start}}}$  means the start point of the string,  $P_{i_{\text{end}}}$  means the end point of the string,  $c_i$  means the cross section of the string, and  $v_i$  means the printing speed.  $v_i$  is conceptually unnecessary, but it is useful in implementing

(printing) the string.

Describing a deformation using Cartesian coordinates is sometimes useful, and thus the following function is defined.

`deform_xyz( $fd(x, y, z), fc(c, x, y, z), fv(v, x, y, z)$ )`

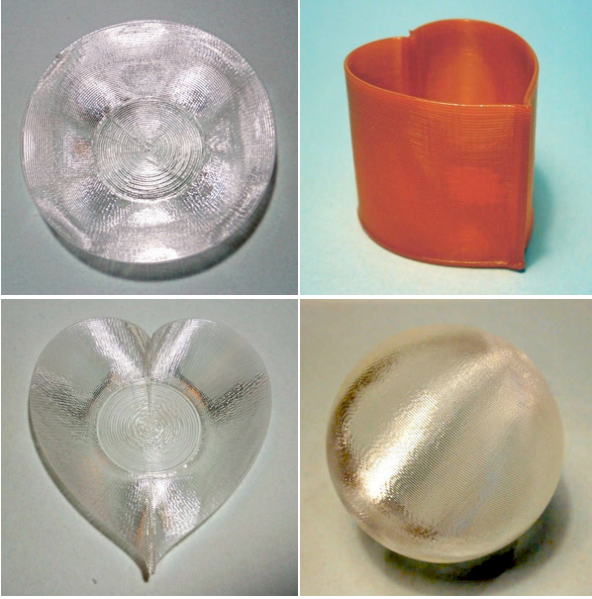


Figure 2: Objects printed by the helical/spiral 3D-printing method

Function  $fd(x, y, z)$  (i.e., the first argument) maps a location  $(x, y, z)$  to a new location  $(x_1, y_1, z_1)$ , so it returns three values. Function  $fc(c, x, y, z)$  (i.e., the second argument) maps a cross-section at  $(x, y, z)$  to a new cross-section at  $(x_1, y_1, z_1)$ . Function  $fv(v, x, y, z)$  (i.e., the third argument) maps a printing speed at  $(x, y, z)$  to a new printing speed at  $(x_1, y_1, z_1)$ . Function  $fc$  must be monotonically increasing about  $c$  and function  $fv$  must be monotonically increasing about  $v$ . Theoretically, any mapping can be specified for  $fd$ ,  $fv$ , and  $k$ . However, they must at least be continuous and smooth to get a correct printing result. There may have to be other conditions on these functions. Such conditions will be described in future work.

It would be better if the cross section could automatically be optimized; however, it is currently difficult. Therefore, the cross section must be manually specified in the method proposed in this paper.

A cylinder coordinate is more useful for describing a deformation, especially when axisymmetric models are deformed, so the following function is defined.

`deform_cylinder( $fd(r, \theta, z), fc(c, r, \theta, z), fv(v, r, \theta, z)$ )`

Function  $fd(r, \theta, z)$  (i.e., the first argument) maps a location  $(r, \theta, z)$ , which is expressed in cylinder coordinates, to a new location  $(r_1, \theta_1, z_1)$ . Function  $fc(c, r, \theta, z)$  (i.e., the second argument) maps a cross-section at  $(r, \theta, z)$  to a new cross-section at  $(r_1, \theta_1, z_1)$ . Function  $fv(v, r, \theta, z)$  (i.e., the third argument) maps a printing speed at location  $(r, \theta, z)$  to a new speed at  $(r_1, \theta_1, z_1)$ . The same monotonicity conditions as `deform_xyz` exist for  $fv$  and  $fc$  for `deform_cylinder`. Functions  $fd$ ,  $fv$ , and  $fc$  must be continuous and smooth.

### 3. Method Selection

This section describes methods for adding pictures, characters, or textures to surfaces of objects printed by the helical/spiral printing method and selects one of them, i.e., to vary the cross section of the filament by changing the print-head motion speed, for practice.

The alternatives are the following three methods.

- To give surface structure to the parts used for assembling, which are predefined by modeling tools. Each part may have optional parameters to map surface structure to the surface.
- To add surface structure by deforming objects.
- To vary the cross section of the filament on the surface when printing it.

The third method was selected for the following reason. It is not easy by using the first method based on predefined parts to prepare parts that are applicable to every application. The second method based on deformation may be suited for certain purposes; however, a deformation changes not only the shape of the surface but also changes the shape of other portion of the object, but it is not desirable. The third method based on cross section, thus, seems to be the best because it is easy to map each part of a structure to a string, which is a part of the object, and this method affects only the surface of the object. This method can probably generate fine structures, although it is not suited for generating large and deep structures.

This method can be called the *extrusion modulation method*; that is, the process of filament extrusion is *modulated* by pictures, characters, or textures.

Two methods are available for extrusion modulation.

- To vary the extrusion speed of filament.
- To vary the print-head motion speed.

The second method was selected for the following reason. The first method directly controls the amount of filament; however, the author decided to use the second method because it is better in response time. In 3D printers, the delay between the motion of the extruder that extrude the filament and the motion of filament at the nozzle, i.e., the tip of the print head is large. It may take several seconds. The response is, thus, slow. Print heads of 3D printers are usually heavy so they have large inertia; however, the response of the print heads are still much better than the filament response.

### 4. Method for Modulating 3D-printed Surface

This section describes a method for modulating a surface of a direction-specified model of a 3D-printed object by varying the head motion (and/or the extrusion speed). The original and modulated models are represented by sequences of strings described in Section 2. The original model is modulated by using a bitmap and the modulated model is generated.

**Figure 3** outlines the modulation process. This method converts the original strings  $S_i$  to new strings  $S_i'$  ( $1 \leq i \leq N$ ). Each string has the cross section,  $c_i$ , and the head

speed,  $v_i$ , as its properties. These values are updated by the modulation. If the corresponding bit is zero, the value of  $c_i$  becomes  $c_0$  and the value of  $v_i$  becomes  $v_0$ . If the corresponding bit is one, the value of  $c_i$  becomes  $c_1$  and the value of  $v_i$  becomes  $v_1$ . If  $v_0 = v_1$ , the cross section is controlled only by extrusion speed. This is *not* the selected method. If  $c_1/c_0 = v_1/v_0$ , the cross section is controlled only by print-head motion speed. This method is selected because the extrusion-speed control mechanism does not respond quickly; that means, it has large latency. (Note that  $c_i$  is not the filament extrusion speed that should be specified in the G-code.)

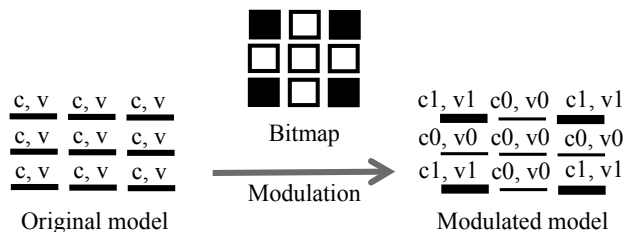


Figure 3: Modulation by a bitmap

Two additional techniques are described. First, if the bitmap is multi-valued (e.g., the range of the values is 0, 1, 2, 3, or it is continuous), the value of  $c_i$  and  $v_i$  are also multi-valued. However, the contrast, i.e., the value of  $c_1/c_0$ , is restricted to be low because too small or too much extrusion disables stacking filament correctly, so a multi-valued surface structure is not very effective. Second, if a string length is long and the bitmap is very fine, it may have to be divided before mapping the bitmap.

## 5. Experiments

Globes, bowls and dishes, calendars, and so on, were experimentally printed by using a delta-type 3D printer (Figure 4), which is better in non-horizontal printing. Some of them are explained in this section. One example

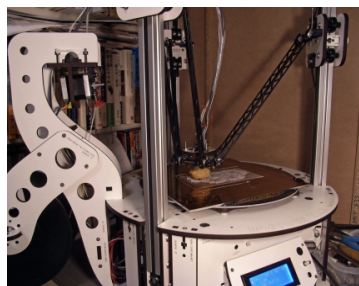


Figure 4: The delta-type 3D printer used (Rostock MAX)

is a globe, which is created by modulating a sphere by a world map. The other example is a bowl or calendar modulated by characters. All the samples in this section and in Section 2 are available from a Web site (<http://store.shopping.yahoo.co.jp/dasyn/>).

### 5.1 Globe and picture modulation

A globe can be created by modulating a sphere by a world map. If a plain is modulated by a map, the map is printed as is. However, if a sphere is modulated by a world map created by equidistant cylindrical projection, a globe is generated. Figure 5 shows a binary-valued world map made from a map with equidistant cylindrical projection available at Celsia Motherload (<http://www.celestialmotherlode.net/catalog/earth.php>), which is based on NASA's data. This site contains various

maps made from the data. The size of the map shown in Figure 3 is 300 x 150, so each dot in a bitmap should be mapped to an area with 1.2° of longitude and 1.2° of latitude. Each circle of the globe should consist of 300 strings, and a sphere is generated by 150 circles, and each dot in the map is mapped to a string in the globe.

In this method, each circle is divided to 300 strings; however, the strings are too short near the poles. It may make printing too slow or sometimes it makes too much overload to the printer and it may stop printing. To solve this problem, the strings or dots close to the poles must be thinned. A method for thinning data is to modify the model; that is, to reduce the number of strings near the poles. However, this method makes the model complicated. Another method, which is considered to be better, is to thin the data when converting the model to G-code. By using this method, it is not necessary to modify the model, so the model can be kept simpler.



Figure 5: Binary bitmapped map of size 300 x 150.

Figure 6 shows a globe printed by the method described above with pure and transparent polylactic acid (PLA). A video on the printing process (<http://youtu.be/>

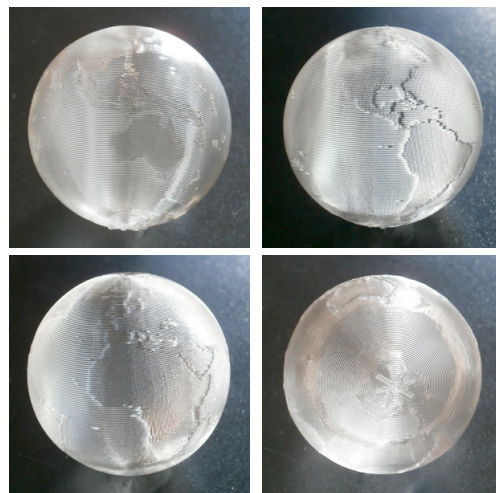


Figure 6: Globe (Modulated sphere, 50-mm diameter).

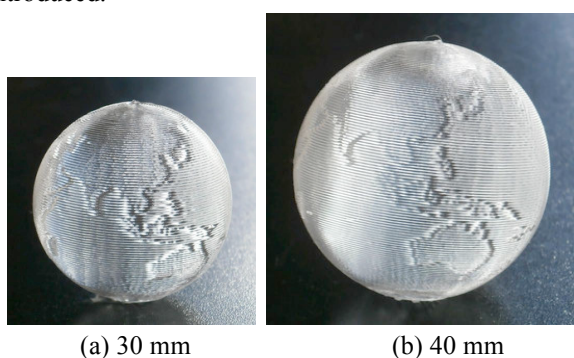


YWxlvqig2-o) and samples (<http://store.shopping.yahoo.co.jp/dasyn/1201-03.html>) are available. The diameter of this globe is 50 mm. The land is thicker (i.e., printed slower) than the sea in this globe. The contrast ( $v_1/v_0 = c_1/c_0$ ) is 1.3 to 1.4. If it is larger, the printing process easily fails at the bottom (in Antarctica). Transparent material is used because the fine surface structure can be observed better.

The star mark at the bottom (shown in the last photo in Figure 6) is part of the support (the actual size of the support is 60 x 60 mm). Although no support in conventional sense is required, it is necessary to stabilize the printing process by adding it because it is not possible to print it by supporting only at the single point at the bottom.

This globe was not damaged by several times of free fall test from approximately 1.5-m height; however, detailed test has not yet been conducted.

Figure 7 shows globes of other sizes, i.e., 30- to 80-mm diameters (<http://store.shopping.yahoo.co.jp/dasyn/3db0f5baf2.html>). All of them are rather small because a large size of globe with a single-layer thickness is too weak. The largest one may break down if dropped to the floor and it may be easily broken by crushing by hand. To increase the thickness and strength, a 5- or 6-axis printer [5] is required. Otherwise, the helical structure must be abandoned and layer-to-layer connection, which easily causes superfluous filament extrusion, must be introduced.



(a) 30 mm

(b) 40 mm



(a) 80 mm

Figure 7: Globes (Modulated sphere, 30- to 80-mm diameter).

## 5.2 Dishes and cups modulated by characters

Figure 8 shows a bowl modulated by characters and Figure 9 shows a calendar consists of six helices, i.e., two

months per helix. The diameter of the bowl is 50 mm and that of the calendar is 45 to 60 mm. Because they are small, 5 x 7 dot-matrix alpha-numeric letters are used for the modulation.



Figure 8: Modulated bowl



Figure 9: Calendar

## 6. Conclusion

A method for modulating the printing process of helical/spiral FDM 3D-printing method to add pictures, characters, or textures on the surface is proposed in this paper. This method can only create thin concave-convex structures; however, the resolution can be the filament size (i.e., 0.4 mm or less), and they never unstuck. This method was successfully applied to print small globes, bowls, calendars, and so on.

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