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METHOD OF DESIGNING, PARTITIONING, AND PRINTING 3D OBJECTS WITH SPECIFIED PRINTING DIRECTION

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ABSTRACT

Although 3D objects to be printed may have "natural direction" or intended direction for printing, most 3D printing methods slice and print them horizontally. This causes staircase effect on the surface and prevents expression of the natural or intended direction; that is, the natural direction and the printing direction contradict. This paper proposes a methodology for direction-specified 3D printing and methods for designing, partitioning, and printing 3D objects with specified printing direction using a fused deposition modeling (FDM) printer. By using these methods, printed objects do not only have unnatural steps but also enables to express the direction explicitly. By developing and evaluating a set of methods based on this methodology, chained rings of an Olympic symbol are designed, partitioned, and printed by a delta-type 3D printer, which is cheaper but can move quick vertically. The rings were well designed and printed rings look well. Although there are still several unsolved problems including difficulty in deciding part partition points and weakness in the partition points, this methodology will probably enable new applications of 3D printing, such as 3D calligraphy.

INTRODUCTION

In additive manufacturing (AM) processes, two problems are caused by horizontally-layered printing. 3D printers print objects horizontally, i.e., layer by layer. A print head of a fused deposition modeling (FDM) printer almost never moves vertically except when it moves to the next layer. Problems that may be caused by this feature are as follow. The first problem is the *staircase effect*. That is, if the surface of objects is not horizontal, horizontally-layered printing generates non-smooth surface. The second problem is that the "strength" of printed objects is usually weaker than printed objects that were aligned horizontally.

Moreover, horizontally-layered printing disables many possibilities of FDM printers that may be able to generate natural or intentional texture on the object surface (and potentially inside the object, which may be visible when the object is transparent). 3D printing can be used not only for rapid prototyping, in which the texture of the artistic impression of printed objects is not very important, but it can also be used for wider applications, such as printing figures or other artistic objects. For example, a printed object, such as hair or grass has natural directions, which are not usually horizontal, the natural direction contradicts with the printing direction. The printing direction is sometimes invisible in printed objects, but it is usually visible in printed objects unless it is intentionally erased, and it can be explicitly controlled. If the printing direction is consistent with the natural or intentional direction, the printed objects can explicitly express the direction and generate artistic texture.

This paper proposes a methodology for printing 3D objects with specified printing direction by using an FMD method. This methodology was briefly summarized in a poster and a short note [2, 3]. This methodology is called the *direction-specified 3D printing methodology*. If the object to be printed has a natural direction, the direction may be detected by the printing system or software. However, the direction is not assumed to be natural in this methodology because it may be unable to decide a natural direction and it is considered to be sometimes useful to decide a direction intentionally. Therefore, the direction, i.e., the printing direction, is explicitly specified at design time in the proposed methodology.

This methodology thus requires (1) a new representation of directed object models and (2) at least four new methods for modeling an object, partitioning the model, generating a tool-path, and printing the object. First, an object is modeled as a model with directions or a "vector field", similar to a magnetic field; that is, each point in the model has a direction. Because this model is different from conventional CAD models and different methods for manufacturing are required, this paper proposes new methods for designing, tool-path generation, and printing methods. In conventional 3D printing, STL (Standard Triangulation Language or Stereo-Lithography) is used for the modeling language; however, because STL-based models are not directed models, STL cannot be used in this methodology unless it is extended to express directed models. This paper thus proposes an alternative representation of objects.

Second, objects are partitioned into smaller parts by two ways. Firstly, objects may have to be partitioned because they may be unprintable because the print head cannot access a “hidden” place. A connected unprintable object may therefore have to be partitioned into two or more printable parts. Secondly, along the specified direction, a directed model should be hashed (partitioned) into strings, which are divided both horizontally and vertically, or in a skewed direction. This partitioning is thus different from conventional slicing. This process is called *hashing*. Conventional slicing methods cannot be used even if the slicing direction is not horizontal because it may contradict with specified directions; that is, different parts of a slice may have different specified directions.

Third, a tool-path is generated from a set of partitioned objects. If the cross section of strings is constant, this process is rather easy. However, it may be more difficult if the shape of strings is more complex. In addition, support materials must be generated in this process.

Forth, a 3D printer prints the object using the tool-path. Because the print head must move to non-horizontal direction, different types of printers, which can print steeply or even vertically, may be required.

The rest of this paper is organized as follows. First, related work is explained. Second, the conceptual outline of the methodology, including methods that are not yet available, is described. Third, a method for designing directed objects is described. Forth, a method for partitioning objects, which is required for printing combined objects, is described. Fifth, a method for generating tool-paths is described. Sixth, a result of an experiment of printing an Olympic symbol is described. Finally, applications of the proposed methods to arts, such as 3D calligraphy, are proposed, and this paper concludes.

RELATED WORK

To eliminate staircase effect (stair stepping effect) and to strengthen non-horizontal objects kinetically, Xuan Song, et al. [1] proposed a method for printing 3D objects using six-axis motions using a Stewart mechanism. They enabled steep or even complete vertical printing. They also mentioned to 3D printing with non-uniform layers. However, their method is based on normal direction-less CAD model. They did not use this method for printing models with specified directions.

CONCEPTUAL OUTLINE

This section outlines the proposed methodology for printing a 3D object with specified printing direction.

Four steps

The process consists of four steps: field-oriented modeling, model partitioning, field-based tool-path generation, and non-horizontal 3D printing (**Fig. 1**). These steps are explained more below.

Field-oriented model and modeling

In the field-oriented modeling step, an object model with vector field is created. It is represented by a modeling language that can express a vector field. It is an extension of conventional solid model. A vector is defined at each (3D) point in the object.

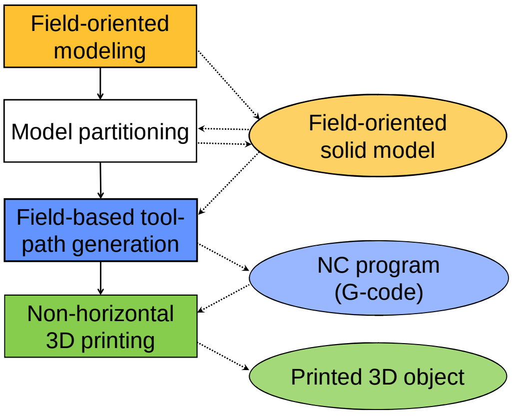


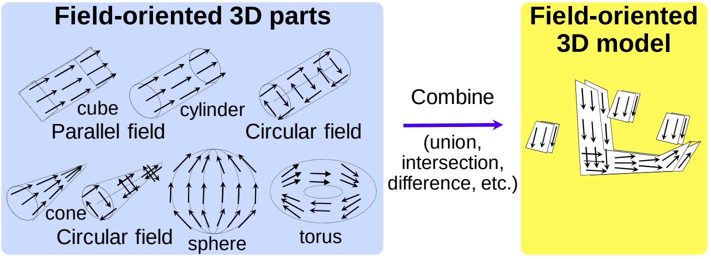
Figure 1: Whole process of design and printing

A field-oriented model may be created by using the following two ways: field-oriented 3D CAD and field-oriented 3D painting. For the purpose of field-oriented modeling, two methods may be available: parts combination and magnetization.

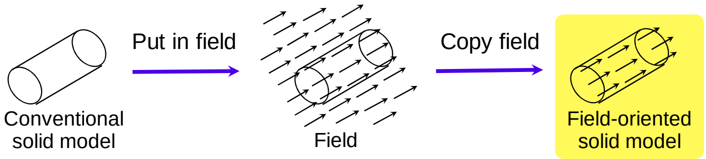
By using the first method, i.e., *parts combination*, which is illustrated in **Fig. 2**(a), the designer designs and combines 3D parts with “vector field” using a field-oriented 3D CAD tool. The combination operations are similar to normal union, intersection, difference, and so on. However, these operations must define the methods of computing vector field from the vector fields in the original objects.

The second method, i.e., *magnetization*, is illustrated in Fig. 2(b). By using this method, the designer first design normal 3D solid model using a conventional 3D CAD tool, and put the object in a vector field selected by the designer. When the designer specifies “copy field” operation, the field is copied into the object.

The second way of modeling, i.e., *field-oriented 3D painting*, is analogical to 2D painting, which is widely used in personal computers. Similar to a 2D painting tool that uses 2D pointing device, a 3D painting tool uses 3D pointing device. A human body tracking device, such as Microsoft Kinect, or sensors such as accelerometers used in Nintendo Wii can be used as 3D pointing device. The width and shape of the painting tool (such as 3D brush) can also be specified by a



(a) Parts combination in field-oriented 3D CAD



(b) Magnetization in field-oriented 3D CAD

Figure 2: Three potential design methods

human hand (fingers), in the case of a human body tracking, or by pressure sensors, in the case of accelerometer-based method. In contrast to normal painting tools, field-oriented 3D painting tools record the direction of motion, and generate field vectors for each point in the painted object.

Model partitioning

In the model partitioning step, the designed model is partitioned to a list of strings (fragments) that can be printed. This model partitioning process consists of two steps. The first step is called *printability enhancement*. In this step, a set of objects with specified printing direction, which might not be printable because the print head cannot access to locations to be printed, is tried to be converted into a printable set by splitting them to smaller parts in this step. However, not all set of objects can be made printable.

A more detailed explanation of printability enhancement follows. Similar to conventional CNC, some objects are not printable because of their shapes. The range of printable shapes in the directed 3D printing is narrower than that of conventional 3D printing. However, the range can become wider by changing printing order. An example is shown in **Fig. 3**. The left figure shows the original shape, a chain with two rings, which is not printable. It becomes printable if one of the rings is divided into two parts and the printing order is changed as shown in the right figure.

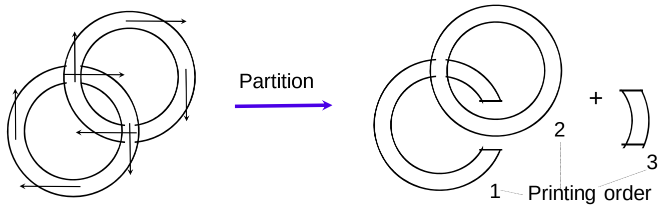
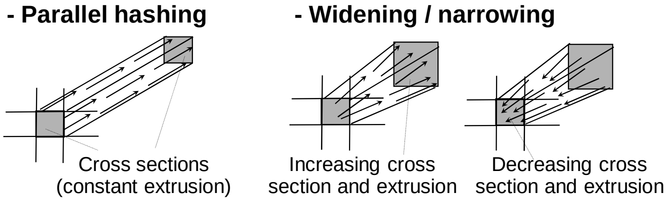
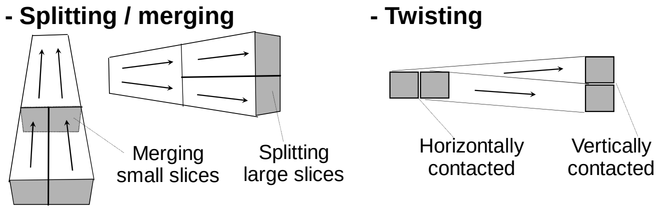


Figure 3: Printability enhancement

The second step is called *hashing*. In a tool-path generation process, an object is "hashed" along the field vectors as shown in **Fig. 4**(a). Each hashed string is intended to be printed at once; that means, the strings can be regarded as filaments. This process is completely different from "slicing" in conventional 3D printing especially when the field vectors are not in parallel.



(a) Basic hashing methods



(b) Advanced hashing techniques

Figure 4: Hashing

If the object has parallel field as shown in the left half of this figure, it is hashed in parallel. The hashed object consists of strings that can be easily filled with filament by constant extrusion. However, if the field vectors are not in parallel, advanced hashing techniques such as *widening* or *narrowing*, as shown in Fig. 4(b), are required. Widening means "increasing the cross section of filament", and narrowing means "decreasing it by controlling the velocity of extrusion or the velocity of head motion".

If the cross section of strings changes rapidly along the direction, the strings must be split or merged as shown in the left half of Fig. 4(b). If a string is vertically widening and horizontally narrowing, or vice versa, another method called *twisting*, can be applied (see the right half of this figure). By twisting, two or more horizontally-arrayed strings at a location are vertically-arrayed at another location.

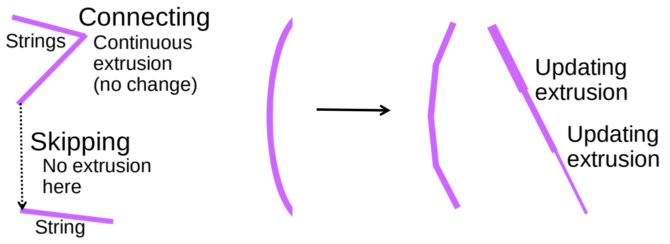
Field-based toolpath generation and extrusion control

In the field-based tool-path generation step, not only tool-path is generated, but also the amount of extrusion is calculated for each string. A hashed field-oriented solid model is inputted and a normal NC program, such as a G-code based program, is outputted in this step. Although conventional languages for describing NC programs are used, the algorithm of this tool-path generation is completely different from "slicing" algorithms in conventional 3D printing.

A tool-path is generated by ordering strings by "connecting" or "skipping". By "skipping", the head moves from a string to another without extrusion. By "connecting", two strings are connected if they are neighboring (**Fig. 5**(a)). If two strings share an end point or the end points are very close, filament is continuously and normally extruded. To connect strings, the printing direction of a string may be reversed. However, if they do not share an end point, extrusion is suppressed between the end points.

If the string is curved, it is approximated by a set of short line segments because most 3D printers cannot move along a curve (Fig. 5(b)). If the cross section of a string is constant at any location, the amount of extrusion should be constant. In contrast, if a string is widened or narrowed, the amount of extrusion should be increased or decreased in a stepwise manner to fill the string (Fig. 5(c)).

If the directions of an object (bottom) is not horizontal, support material is usually required. In such cases, the support must be printed before printing the object. Support material may also be required inside the object or between parts of the object.



(a) Skipping and connection
(b) Approximation by line segments
(c) Widening/ narrowing

Figure 5: Tool-path generation

Non-horizontal 3D printing

In the non-horizontal 3D printing step, an object with specified direction is created. Conventional 3D printers may be used for this process because a G-code program can express non-horizontal motions and conventional 3D printers execute it correctly.

To increase the range of printable objects, a needle-shaped nozzle or five- or six-axis print head will work (**Fig. 6**). In addition, to move the head to vertical direction rapidly, a special type of head-motion mechanism may be required.

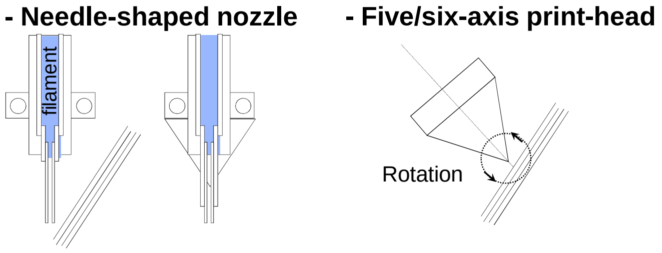


Figure 6: Heads for steep/vertical printing

PRACTICAL METHODS

Most of the techniques described in the previous section are not yet available. This section describes a set of methods for printing objects with specified directions, which are still being developed but are partially available now.

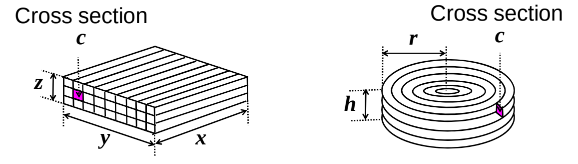
Model specification and design methods

Two practical methods are proposed: a model specification method and a design method for this type of models. In the first method, which is called the *hashed-model specification method*, instead of specifying a solid model with vector field, shapes that consist of strings are specified; that is, they are pre-hashed. This is a method of a partial combination of the field-oriented modeling, the model partitioning, and the tool-path generation. The shapes may be a cube, cylinder, cone, sphere, or any other directed shape, and they are hashed in parallel, in circles, or in other ways (see examples in **Fig. 7**(a) and Fig. 2(a)). If the strings are (the field is) in parallel, the cross section of strings can be constant, so the cross section or the diameter of the strings is specified as a parameter. For example, if the shape is a cylinder with parallel or circular strings, the following parameters are specified:

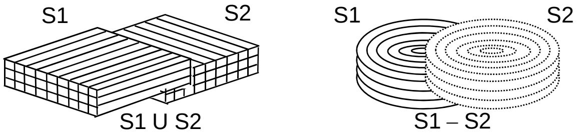
Radius of the cylinder: ***r***,
Height of the cylinder: ***h***, and
String cross section: ***c***.

If the strings are not in parallel, then splitting, merging, or twisting is required. However, these techniques can be automatically selected, so no additional parameter is required.

In the second method, which is called the *hashed parts combination method*, shapes are combined by using normal set operations, i.e., translation, rotation, union, intersection, differentiation, and so on. Although normal set operations are commutative, operations of directed shapes are not commutative; if S1 and S2 are shapes, shapes S1 ∪ S2 and S1 ∩ S2 inherits strings from S1 where S1 and S2 are overlapping. In a difference S1 – S2, S2 can be an undirected (normal) shape (Fig. 7(b)). In addition, a 3D shape with strings can be created by 2D shape with strings by using sketch operation.



(a) Hashed parts



(b) Combination of hashed partes

Figure 7: Hashed parts for combination

Partitioning

Automatic partitioning processes are omitted in this set of methods because of the following two reasons. The first reason is that, because shapes that consist of pre-hashed strings are used, there is no need to hash the shapes.

The second reason is that, because no method for automatic printability enhancement has been developed, objects must be partitioned manually so that they are printable; that is, printability enhancement must be done at design time. Automatic partitioning is difficult because it strongly depends both on the shape of objects and on the shape of the print head. **Fig. 8** shows a rather simple case. The lower part, which is light, and the upper part, which is dark, are split by skewed surfaces because the upper part must be printable by the print head. The shape of a print head and its support is usually quite complex and it may make printability enhancement difficult unless the print head is not a needle-like or five- or six-axis one.

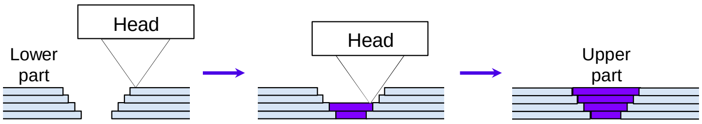


Figure 8: Partitioning for cone-shaped head

Tool-path generation method

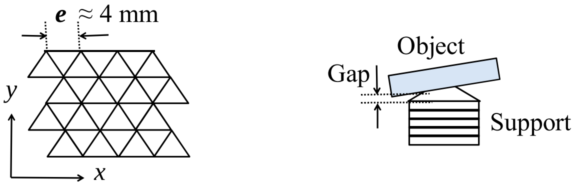
A tool-path generation method using the maximum object-height is proposed. Strings should be sorted to minimize the summation of skipping distances. As many strings are connected as possible. However, skipping cannot usually be eliminated. When skipping from (x_1, y_1, z_1) to (x_2, y_2, z_2), there may be printed object (strings) between these points. Therefore, to avoid collisions in this method, the print head is first moved vertically to the maximum height of the object, z_{max}, i.e., to (x_1, y_1, z_{max}), second moved horizontally to (x_2, y_2, z_{max}), and finally moved vertically to (x_2, y_2, z_2). If the printer can move the head quickly to vertical direction, this method works well.

Extrusion should be turned off while skipping; however, because there is delay between filament control and extrusion from the nozzle, it may make high-speed printing difficult. In this proposed method, therefore, the print head extrudes constantly but it moves quickly to the next string position. Although this method may create thin strings, it works mostly well.

Support generation method

A method for generating triangle-shaped support is described. Only the bottom of the object is supported by this method; that is, no support is generated inside the object. This method prints repetitive patterns with small equilateral triangles (**Fig. 9**(a)). The same horizontal shapes are layered and they are printed layer by layer. The edge size of the triangles is around 4 mm. The reason why triangle pattern is used is that it is less direction-dependent than conventionally used mostly parallel patterns. Printing direction of support can usually be selected with taking that of object into account. It is usually orthogonal to that of object. This method is good when object printing direction can be selected by the slicer. However, in the proposed method, the printing directions are specified in the design, so a direction-independent pattern works better. The number of layers is calculated for each triangle edge. The height of the lowest point of the object (strings) near the edge is calculated, and the number of layers is decided using this height (Fig. 9(b)).

It is often necessary to skip the head, i.e., to move the head without printing a triangle edge, because the support height is not constant. However, to maximize the printing velocity, the extrusion velocity may have to be constant.



(a) Support pattern (b) Calculation of support height

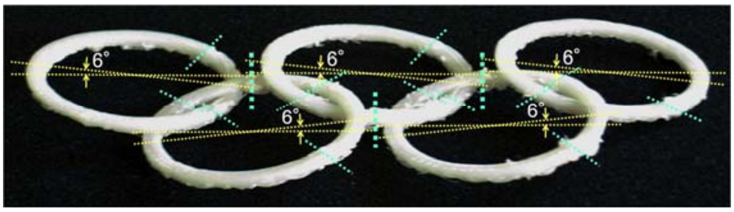
Figure 9: Support generation method

EXAMPLE: OLYMPIC RINGS AS A CHAIN

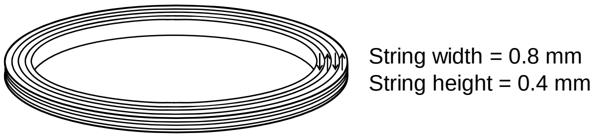
To evaluate the method described in the previous section, chained rings of an Olympic symbol as a chain were designed and printed by a 3D printer called Rostock MAX. Because no tools for the direction-specified 3D printing were available, all the methods described in the previous section were built into a Python program. Each step is explained as follows.

Design

An Olympic symbol can be regarded as a chain with five rings, which is shown in **Fig. 10**(a). This photo shows a product using ABS filament. There is no room between rings; that is, the neighbor rings are touched because no method for internal support had been developed. A ring could be designed by calculating a difference of two cylinders, which are more primitive parts. However, to simplify the program, a hashed ring was given instead (Fig. 10(b)). Moreover, because printability enhancement was difficult for this shape, each ring was designed as a collection of two or more ring fragments. The fragments are connected at the break lines drawn in Fig. 10(a). The thick break lines in this photo show the most difficult partitioning points. The reason why it is difficult to decide the splitting surfaces for these points is that, because the rings are close each other, it is difficult not to touch the neighbor ring when printing a ring even if the ring is partitioned and sorted by the printing order. The splitting surface must thus have been carefully chosen. Other partitions can probably be automated. The center of each fragment is first placed at the point of origin, i.e., (0, 0, 0), then translated and rotated to get a skewed ring fragments.



(a) Whole chain



(b) A hashed ring

Figure 10: Olympic rings as a chain

Tool-path and support generation

Because enough information on tool-path generation is given in the previous section, no more description is necessary here. So only the support generation is explained more.

The triangle size of support should have been carefully decided. The triangle size used for ABS filament was 4.8 mm and that for PLA filament was 3.8 mm. These sizes were determined after trial printings.

Figure 11(a) shows a support printed using ABS. The print direction for this support was mostly horizontal, so there are many horizontal thin strings. It was difficult to avoid them. It would be better to optimize the printing order. Because the thin strings prevent overlooking the shape of the support, Fig. 11(b) shows a support that thin strings are mostly removed from. If

(a) Printed support (with thin strings)

(b) Printed support (Thin strings are manually removed)

Figure 11: Support for the Olympic rings

the triangle size is larger, the filament sometimes falls into triangles and the shape of rings become inexact. A finer pitch is required for PLA because it is softer than ABS at printing temperature; that means, PLA filament is easier to fall into triangle holes. It takes approximately 24 minutes to print whole support. It is much longer than print time of rings, which is approximately 10 minutes. This support and all the parts are printed without a human intervention.

Non-horizontal printing and print result

The support and the rings were printed by Rostock MAX (**Fig. 12**), which is a delta-type printer (i.e., which uses parallel links). Delta-type printers are good for direction-specified 3D printing because the heads can quickly move vertically. The printing process was demonstrated at Maker Fair Tokyo 2013 [4] and a video was uploaded to YouTube [5].

An example of printed rings with support is shown in **Fig. 13**(a). The shapes of rings are good, but there are many thin strings and some of them are stained; that is, black material can be seen on thin strings. This is caused by thin strings stuck to the print head and carbonized.

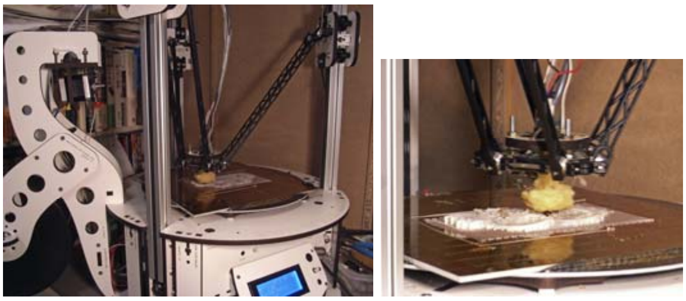


Figure 12: Printing by Rostock MAX

(a) Rings and support

(b) Separated ring parts (c) An error by lacked support

Figure 13: Print result

The result is evaluated as follows. Printed rings look mostly good. The measurement results of the rings are shown in **Table 1**. Each ring is designed to consist of four 0.4-mm layers and each layer is designed to consist of four 0.8-mm width arcs. As shown in this table, the average height of the rings is 44% larger than the designed height probably because the lower layers of the rings were not completely supported by the support. To make the height more accurate, the support method must be improved. In contrast, the outer diameters are slightly smaller than the designed value probably because ABS shrinks by cooling. Except this systematical error, the diameters can be evaluated as sufficiently accurate.

Table 1. Measurement results of rings

Item	Design (mm)	Measured value (mm)	Ratio (M/D)
Ring height	1.6	2.3 ± 0.2	1.44
Outer diameter	40.4	39.9 ± 0.4	0.988
Inner diameter	34.0	34.0 ± 0.3	1.0

Although rings were printed mostly well, sometimes contain several defects. Most of partitioned rings are well connected; however, some of them do not stick to each other well. In such cases, they easily become separated (Fig. 13(b)). It is necessary to use needle-like head or five- or six-axis head to solve this problem. Support is usually printed well and works well, but, because the printing velocity is high, sometimes part of support lacks. Lacked support generates incorrect shapes such as the one shown in Fig. 13(c). This defect will not occur if the support is complete; it may be necessary to print support more slowly.

APPLICATIONS

The proposed methodology and methods may be more suited for artistic applications rather than conventional industrial applications. When printability enhancement is not required, the direction-specified design and printing method is suited for industrial application, i.e., rapid prototyping because this method kinetically strengthens printed objects. However, as described in the introduction, this method makes objects visually better, so it can be applied to artistic applications. In addition, because connection of split fragments makes the kinetic strength of objects weaker, this method might not be better for industrial applications when printability enhancement is necessary and a better connection method is not available. Therefore, artistic applications seem to be more promising.

A potential artistic application is 3D calligraphy; however, the proposed methodology has not yet applied to this application. There are two approaches on 3D calligraphy. The first approach is to copy characters written on a paper to metal, such as iron. For example, Sisyu (Shishu), who is a Japanese calligrapher, in collaboration with SAURS, is creating many 3D calligraphies [6] (**Fig. 14**(a)). The second approach is to design 3D characters. The society for 3D calligraphy displays such 3D characters [7]. Another example of the second approach can be seen in a city (Fig. 14(b)) or exhibitions. The direction-specified 3D printing may contribute to both approaches. It may

(a) An iron-based one by Sisyu (b) A 3D-character sculpture

Figure 14: Conventional 3D calligraphy applications

enable new artistic expressions in the first approach, and a set of method including field-oriented 3D printing may also introduce new expressions to the second approach.

Other applications may be arisen from personal use of 3D printers, such as use in hobbies. However, it is a future issue.

SUMMARY AND CONCLUSION

This paper proposed a methodology for direction-specified 3D printing and methods for designing, partitioning, and printing 3D objects with specified printing direction using a fused deposition modeling (FDM) printer. Conceptually, the process consists of four steps, i.e., the field-oriented modeling, the model partitioning, the field-oriented tool-path generation, and the non-horizontal 3D printing steps. To implement this methodology, however, the hashed-model specification method, which is a partial combination of three of the above steps, and several methods for partitioning and supporting are proposed. These methods do not only avoids unnatural staircase effect on printed objects but also enables to express the direction explicitly.

To develop and to evaluate a method based on this methodology, chained rings of an Olympic symbol are designed, partitioned, and printed by using the hashed-model specification method. In this process, a hashed model was used, a tool-path was generated by connecting hashed strings and by controlling filament extrusion and head motion, and printed by a delta-type 3D printer. The Olympic rings were well designed and printed rings look well. However, although the shape of the rings is rather simple, there are still several unsolved problems including difficulty in deciding partition points and weakness in the partition points.

No killer applications have been found, but artistic applications such as 3D calligraphy seem to be promising. This paper suggests a limited range of applications. However, it will be used in more new applications.

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