International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:9, No:4, 2015

Natural-Direction-Consistent 3D-Design and Printing Methods

Yasusi Kanada

Abstract**—**Objects are usually horizontally sliced when printed by 3D printers. Therefore, if an object to be printed, such as a collection of fibers, originally has natural direction in shape, the printed direction contradicts with the natural direction. By using proper tools, such as field-oriented 3D paint software, field-oriented solid modelers, field-based tool-path generation software, and non-horizontal FDM 3D printers, the natural direction can be modeled and objects can be printed in a direction that is consistent with the natural direction. This consistence results in embodiment of momentum or force in expressions of the printed object. To achieve this goal, several design and manufacturing problems, but not all, have been solved. An application of this method is (Japanese) 3D calligraphy.

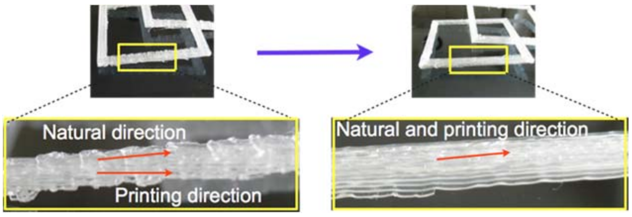
Keywords**—**3D printing, Three-dimensional printing, Solid free-form fabrication, SFF, Fused deposition modeling, FDM, Additive manufacturing

I. Problems to Be Solved

An object to be printed, such as a collection of fibers, may have "natural direction" in the shape. Fig. 1 shows several examples. A leaf has leaf veins, each of which has a natural direction. Each part of human hair and Chinese or Japanese calligraphy also has a natural direction too.

Fig. 1 Natural direction in shape (from Wikipedia/Wikimedia[1])

The printing direction of fused deposition modeling (FDM) 3D printers, which is most popular in cheaper 3D printers such as Makerbot [1] and RepRap [2], however, may contradict with the "natural direction" because the print head always run horizontally. This contradiction causes so-called "staircase effect", and both the shape and the intensity of the printed object are not good (see Fig. 2 (a)). The printed shape should be close to Fig. 2 (b).



(a) Conventional method (b) Natural-direction-consistent method

Fig. 2 Printing direction vs. natural direction in normal and natural-direction-consistent 3D printing

II. "Field" Based Solution

To solve the above problem, a "field" based solution is proposed here. To model objects with "natural directions", and to slice and to print objects in the "natural direction", objects are designed and printed following the three steps below (see Fig. 3).

1) Field-oriented modeling
2) Field-based tool-path generation
3) Non-horizontal 3D printing

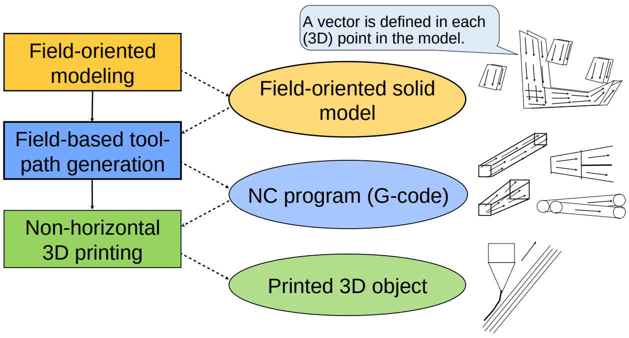


Fig. 3 Three steps for natural-direction 3D printing

The field-oriented modeling outputs field-oriented solid model, which is an extension of conventional solid model. A vector is defined at each (3D) point in this model.

The field-based tool-path generation inputs a field-oriented solid model and outputs a normal computerized numerical-control (CNC) program, such as a G-code [5] based program. The algorithm of this tool-path generation is completely different from "slicing" algorithms in conventional 3D printing.

Yasusi Kanada is with Dasyn.com, Nakano-ku Yayoi-cho 4-2-16, Tokyo, 164-0013, Japan (e-mail: yasusi@kanadas.com).

* This paper is an extended version of a poster [3]. Several methods described in this paper are explained in a succeeding paper, which has already been published [4].

[1] The left photo from http://en.wikipedia.org/wiki/Leaf, the middle photo from http://commons.wikimedia.org/wiki/Category:Hair, and the right photo from http://en.wikipedia.org/wiki/Calligraphy

By the non-horizontal 3D printing, an object with natural direction is created. This process may be performed by a conventional 3D printer because a G-code program can express non-horizontal motions and conventional 3D printers can execute it correctly.

The following three sections explain the above three steps.

III. Modeling Methods

Two methods for field-oriented modeling are proposed here. They are field-oriented 3D computer-aided design (CAD) and field-oriented 3D painting.

A. Field-Oriented 3D CAD

Two methods for field-oriented 3D CAD are proposed. One method is "parts combination" shown in Fig. 4. In this method, the designer combines 3D parts with "field" using a field-oriented 3D CAD tool. The combination operations are based on normal set operations, i.e., union, intersection, difference, and so on. However, these operations must define the methods of computing field from the fields in the parts to be combined.

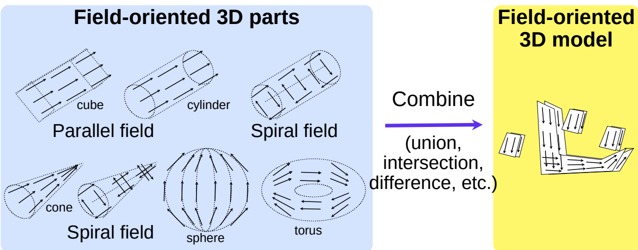


Fig. 4 Parts combination in field-oriented 3D CAD

The other method is "magnetization" shown in Fig. 5. In this method, the designer first design normal 3D solid model using a conventional 3D CAD tool, and put the object in a field selected by the designer. When the designer specifies "copy field" operation, the field is copied into the object.

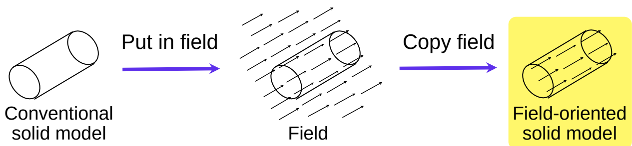
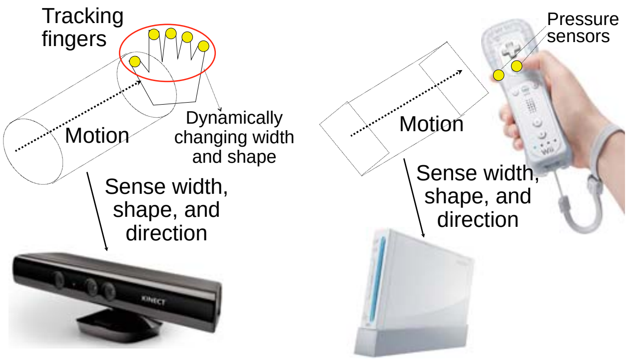


Fig. 5 Magnetization in field-oriented 3D CAD

B. Field-Oriented 3D painting

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 (see Fig. 6). A human body tracking device, such as Microsoft Kinect [6] (Fig. 6 (a)), or sensors such as accelerometers used in Nintendo Wii (Fig. 6 (b)) can be used as 3D pointing device. The width and shape of the painting tool (such as 3D brush) can also be specified by 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.



(a) Painting by using human body tracking (Microsoft Kinect) (b) Painting by using sensors (Nintendo Wii)

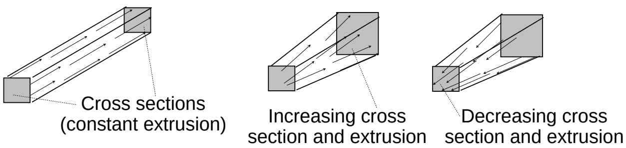
Fig. 6 Field-oriented 3D painting

IV. Tool-Path Generation Methods

A tool path for a 3D printer can be generated using the basic method described in the first section (*A*). Several additional techniques are shown in the second section (*B*).

A. Basic Field-Based Method

In a tool-path generation process, an object is "hashed" along the field vectors as shown in Fig. 7. (Fig. 7 shows a hashed piece.) This process is completely different from "slicing" in conventional 3D printing if the field vectors are not in parallel. If the object has parallel field as shown in Fig. 7 (a), the hashed object consists of strings that can be easily filled by constant extrusion of filament. However, if the field vectors are not in parallel, the strings may widening or narrowing as shown in Fig. 7 (b). In these cases, the amount of extrusion should be increased or decreased to fill the string. However, if the vectors are far from parallel, additional techniques are required. Several techniques for handling such situations are described in the next subsection.



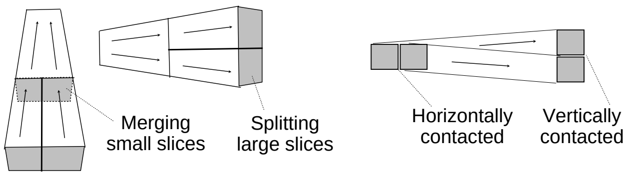
(a) Parallel hashing (b) Widening / narrowing

Fig. 7 Basic field-based tool-path generation method

B. Several Advanced Techniques

If the cross sections of strings change rapidly along the direction, the strings must be split or merged as shown in Fig. 8 (a). The photo included in Fig. 8 shows two examples of split/merged object, which was printed by using Printrbot Plus, a 3D printer. If a string is vertically widening and horizontally narrowing, or vice versa, another method called twisting, can be applied (see Fig. 8 (b)).

International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:9, No:4, 2015

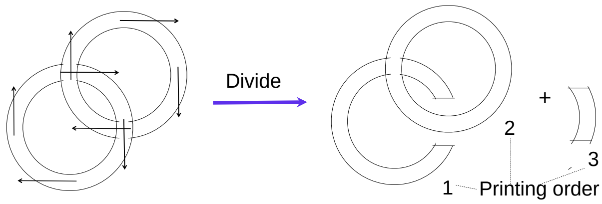


(a) Splitting / merging (b) Twisting

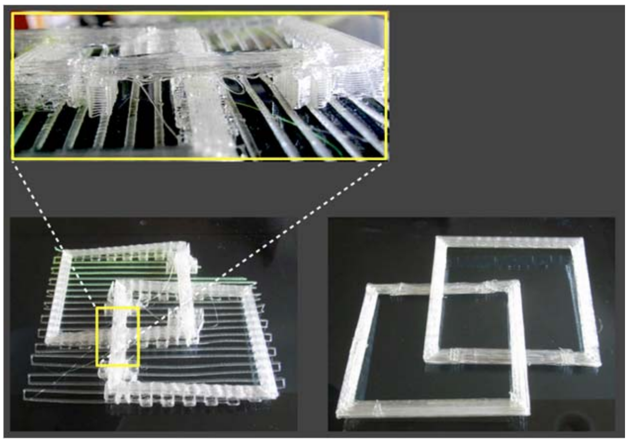
Fig. 8 Several techniques for field-based tool-path generation

C. Divide-and-Reorder Method for Making Unprintable Objects Printable

Similar to conventional CNC, some objects are not printable because of their shapes. The range of printable shapes in the natural-direction-consistent 3D printing is narrower than that of conventional 3D printing. However, the range can become wider by dividing the objects and changing printing order. This method is called the *divide-and-reorder method*.



(a) Method



(b) Example

Fig. 9 The divide-and-reorder method for making unprintable objects printable

Fig. 9 (a) shows the divide-and-reorder method. The original shape, a chain with two rings, which is not printable, is shown at left. It becomes printable if one of the rings is divided into two parts and the printing order is changed as shown at right. Fig. 9 (b) shows an implementation of a rectangle version of this chain, which was printed in natural direction. Because there is currently no tool-path generator, the tool path for this chain was generated by a special-purpose program. The upper photo shows the bridge, i.e., the part 3 of this chain (see Fig. 9 (a)).

V. Printing Techniques

Conventional 3D printers accept G-code for natural-direction 3D printing. However, they cannot print steeply. This section describes the problems and printing techniques to solve them.

A. Problems in Steep Printing

There are two problems that make steep printing difficult or impossible (Fig. 10). One problem is that, because conventional 3D printers are three-axis machines and they extrude only at the bottom, if they print in steep direction, they can collide with printed objects. The nozzle head thus cannot be sufficiently close to printing point. This means there is gap between the nozzle tip and the printing point.

The other problem is that conventional 3D printers cannot usually move quickly along z-axis because they usually use threaded rods for z-axis.

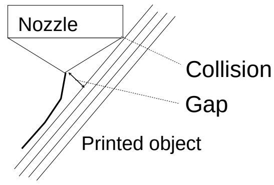
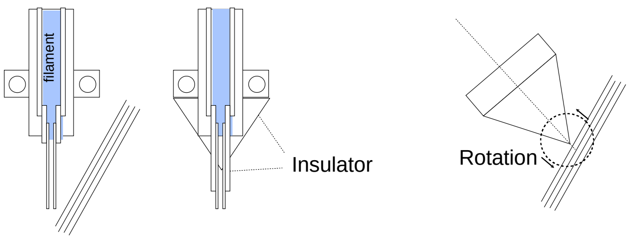


Fig. 10 Problem in steep printing

B. Two Solutions

To solve the first problem, which is much more serious, two methods are available. One method is to use needle-shaped nozzle. Fig. 11 (a) shows this method. If the tip of a nozzle has needle-like shape, it can print in steep angle. However, such as shape of nozzle causes significant decrease of temperature at the tip. Several methods are available to keep the temperature. A method is to cover the tip by insulator as shown in this figure. A needle-shaped nozzle can print in steep angle, but it is difficult for this type of printer to print vertically. However, a printer of this type can be developed by improving a conventional printer.



(a) Needle-shaped nozzle (b) Five-axis print-head

Fig. 11 Two solutions to the problem in steep printing

The other method is to use a five-axis print-head (Fig. 11 (b)). Two additional axes are used for rotating the head. By rotating a print head, it can print vertically or even at downside. However, a printer of this type must be developed mostly from scratch. Xuan Song et al. [7] developed this type of 3D printer.

For the solution to the second problem, see Section VI-C.

VI. Implementation

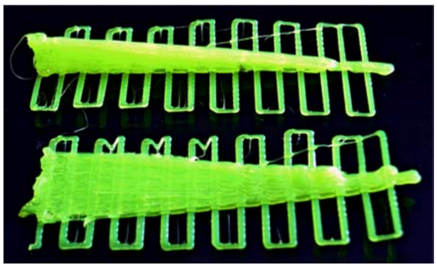
The implementations of natural-direction 3D printing technologies are in very early stages (in 2013).

A. Field-Oriented modeling

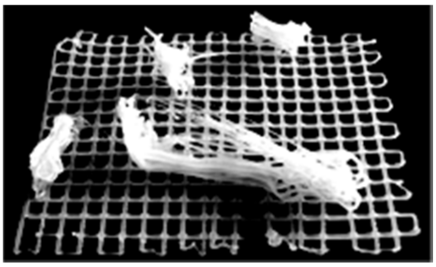
A Kinect-based modeler, which is proposed in Section III-B, is being designed but not yet implemented.

B. Field-Based Hashing

Several hashing algorithms were tested. As described in the previous sections, Fig. 9 (b) already showed testing improvement of printability. Fig. 12 (a) shows splitting and merging. Fig. 12 (b) shows an integration test, a print for 3D calligraphy (a character that means "heart"), which will be explained in the applications section (Section VII).



(a) Splitting and merging



(b) Integration (3D calligraphy)

Fig. 12 Hashing algorithms tested

C. Non-horizontal 3D printing

Non-horizontal printing methods has been tested using Printrbot Plus, and are being tested using Rostock MAX (see Fig. 13). Rostock MAX is a Delta type 3D printer that can move its print head quickly along the z-axis. Therefore, this type of printers can solve the second problem described in Section V-A, i.e., the steep-printing problem.

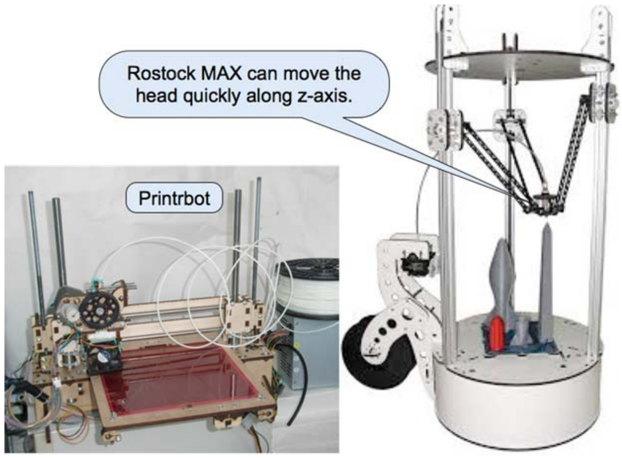


Fig. 13 3D printers used for testing the printing method and techniques

VII. Applications

3D printing has been used for industrial applications, especially for rapid prototyping. However, major applications of natural-direction-consistent printing technologies may be different types of applications.

A. Art: 3D Calligraphy

Natural direction may be more important in artistic applications than in industrial applications. This subsection focuses on applications to 3D calligraphy. Fig. 14 shows a non-directed 3D calligraphy art. Similar artworks by Julien Breton (http://kaalam.fr/) or Rittai-shosho Kenkyukai (the 3D calligraphy research group in Japan, e.g., http://www.cc.kochi-u.ac.jp/~nobukita/kenkyu.html) can be seen in WWW. Directed 3D calligraphy artworks, such as iron-based ones by Sisyu (Shishu) (e.g., http://www.e-sisyu.com/works/2010/04/post-31.html, or http://www.e-sisyu.com/works/2011/03/post-30.html), a Japanese calligraphy artist, can also be seen in WWW. Natural-direction-consistent printing can be applied to directed 3D calligraphy, but it has not yet applied except the author's initial trials such as shown in Fig. 12 (c).

Fig. 14 3D calligraphy example

B. Hobby

Recently, hobbyists use cheap FDM 3D-printers. A pyramid and a polyhedron shown in Fig. 15, in which intuitive directions and printing directions contradict, may be printed in a better way by using natural-direction printing methods.

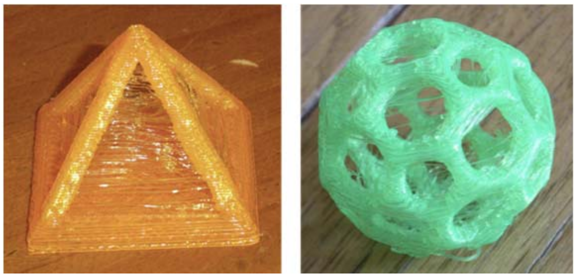


Fig. 15 Hobby application

C. Industrial Applications

There may be industrial applications, but promising applications are not known.

VIII. Concluding Remarks

This paper can be summarized as follows:

- Natural direction of 3D objects can be expressed by FDM 3D-printing using field-oriented/based modeling, hashing, and printing methods.
- The developments of field-oriented/based algorithms and applications are in early stages (in 2013).

The field-oriented modeling, the field-based tool-path generation methods, and non-horizontal 3D printing methods are going to be developed, and they are applied to applications, such as 3D calligraphy.

References

[1] Pettis, B., France, A. K., and Shergill, J., "Getting Started with MakerBot", Maker Media, Inc., 2013.

[2] Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., Palmer, C., and Bowyer, A., "RepRap – the Replicating Rapid Prototyper", *Robotica*, Vol. 29, Special Issue 01, pp 177–191, January 2011.

[3] Kanada, Y., "A Method of 3D Printing which is Consistent with Natural Direction in Shape", *International Solid Free-form Fabrication Symposium 2013*, August 2013.

[4] Kanada, Y., "Method of Designing, Partitioning, and Printing 3D Objects with Specified Printing Direction", *2014 International Symposium on Flexible Automation* (*ISFA*), July 2014.

[5] Kramer, T. R., Proctor, F. M., Messina, E., "The NIST RS274NGC Interpreter - Version 3", National Institute of Standards and Technology (NIST), NISTIR 6556, August 2000.

[6] Zhang, Z., "Microsoft Kinect Sensor and Its Effect", *IEEE MultiMedia*, Vol. 19, No. 2, pp. 4–10, Febuary 2012.

[7] Xuan Song, Yayue Pan, and Yong Chen, "Development of a Low-Cost Parallel Kinematic Machine for Multi-Direction Additive Manufacturing", *International Solid Free-form Fabrication Symposium 2013*, August 2013.

Yasusi Kanada received a B.E. degree in mathematical engineering from the University of Tokyo in 1979 and an M.E. degree in information engineering from the University of Tokyo in 1981. He has been working for Hitachi, Ltd. since 1981. He is a part-time lecturer at Kogakuin University. He worked at Carnegie Mellon University from 1988 to 1990, and at Tsukuba Laboratory of the Real World Computing Partnership (RWCP) from 1992 to 1995. He received a Ph.D. from the University of Tokyo in 1992. He studied programming, programming languages, and emergent computation in the University of Tokyo and in Hitachi, studies and teaches computer networks in Hitachi and Kogakuin University; he also studies new 3D-printing methods for Dasyn.com.