Thickness Control Technique for Printing Tactile Sheets with Fused Deposition Modeling

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ABSTRACT
We present a printing technique that controls the thickness of objects by increasing and decreasing the amount of material extruded during printing. Using this technique, printers can dynamically control thickness and output thicker objects without a staircase effect. This technique allows users to print aesthetic pattern sheets and objects that are tactile without requiring any new hardware. This extends the capabilities of fused deposition modeling (FDM) 3D printers in a simple way. We describe a method of generating and calculating a movement path for printing tactile sheets, and demonstrate the usage and processing of example objects.

Author Keywords
3D printing; digital fabrication; thickness control; haptics; texture

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Advances in digital fabrication techniques such as 3D printers have made it possible to create 3D objects accurately and cheaply. Fused deposition modeling (FDM) printers, in particular, have become famous and available on the market owing to several advantages: ease of use, choice of materials, and low running cost. In association with this advance, new and interesting printing techniques utilizing the characteristics of FDM have been proposed (e.g., printing hair-like structures [3] and spiral printing for generative art [2]). On the other hand, many researchers focus on printing quality because the aesthetics of look and feel is one of the most important features for printed objects [1, 5]. However, to print high-quality objects, most techniques require an expensive printer or long printing time. Objects printed by FDM have a rough and uneven surface, which is called the staircase effect [4].

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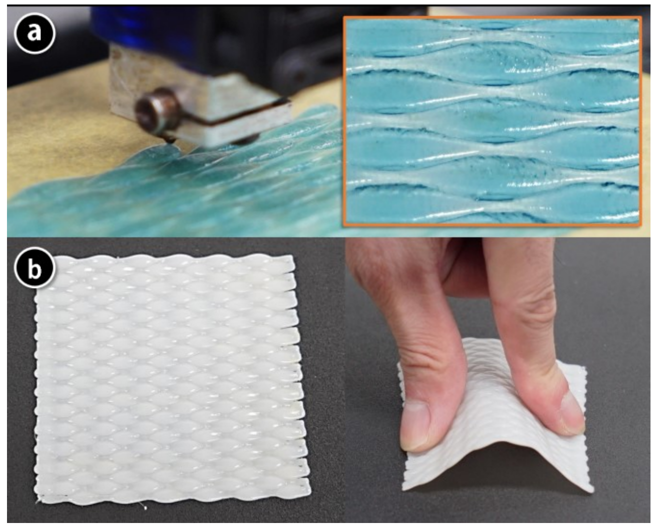

Figure 1. (a) Thickness control technique and close-up. (b) Tactile sheet that combines flexible material.

In this paper, we present a technique that controls the thickness of objects by increasing and decreasing the amount of material and by moving the position of the printer head in the height direction (Figure 1a). Using this technique, printers can dynamically control thickness and output thicker objects without a staircase effect. Our technique consists only of software that can generate corresponding Gcode; this does not require any new hardware or improvements to the printer. We utilize this technique to print a tactile sheet (Figure 1b). This sheet has a smooth tactile sense because it is not printed layer by layer. We demonstrate the usage and post-processing technique of this sheet.

CONTROLLING THICKNESS
The basic idea of controlling thickness is to increase the amount of material extruded during printing. To control the amount of material, we edit Gcode that contains the commands used to control CNC machines including 3D printers. In Gcode, *G1* controls the movement of the printer head and uses an *E* parameter that controls the amount of material extruded between the starting and ending points. We can increase the amount of material used by increasing the *E* value. However, as the thickness of an object increases, the amount of material extruded in one second is increased. This condition of printers is essential for printing at high speed. Thus, the limit on the speed of the stepper motor built into the extruder become problematic. To decide the ideal *F*

parameter (i.e., extrusion speed) for every thickness, we must clarify the features of the extruder.

In order to find the limits of the extruder, we define the *extrusion rate* [mm^3/s], which is the volume extruded in one second. We weigh the extruded object to calculate the extrusion rate using digital scales. We determine the maximum extrusion rate, which is utilized to decide on the ideal extrusion speed, by comparing the requested extrusion with the actual extrusion.

Our technique uses two equations to set parameters. In the equations, let *Height*, *Width*, and *Length* be the scale of an object being printed. The *E* and *F* parameters are calculated as follows:

$$\mathrm{E} = \frac{Height \times Width \times Length}{Cross\text{-}Sectional\ Area\ of\ Filament} \quad (1)$$

$$\mathrm{F} \leq \frac{Maximum\ Extrusion\ Rate}{Height \times Width} \times 60 \quad (2)$$

The maximum extrusion rate is obtained by conducting an experiment. We conducted the experiment using NinjaBot NJB-200 3D printer (http://ninjabot.jp/), and the maximum extrusion rate was approximately 11 mm^3/s. This means that the printer can extrude with the requested rate up to 11 mm^3/s.

Using these equations, we implemented a system that generates Gcode using several parameters: size of sheet, number of bumps, and height of a bump. Gcode generated by our system is divided into micromovements for changing the thickness dynamically (Figure 2). Three-dimensional printers allow their heads to move obliquely, but they cannot control the amount of material corresponding to the height.

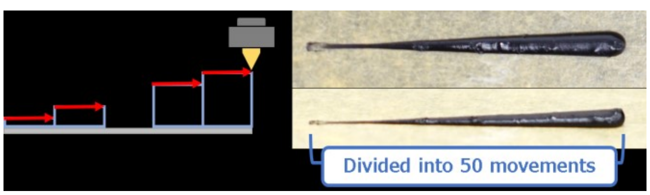

Figure 2. Mechanism of dynamic thickness control.

EXAMPLES

We show the example objects created while applying our technique. To print example objects, we used NJB-200 and set the temperature of the printer head and build platform to the recommended value for each material.

Various Materials We used eight available materials: MakerBot ABS, PolyPlus PLA, flexible, polywood, copper, magnetic iron PLA, carbon, and graphene (Figure 3, top). We confirmed that our basic idea, which changes the thickness of an object dynamically, can be applied to all of the materials. In particular, PLA and flexible filaments were printed cleanly without staircase effects or damage to the aesthetic appearance. As shown in Figure 1b, the flexible one can be bent by hand, and all linear objects in the structure adhere to each other. These materials are suitable for printing

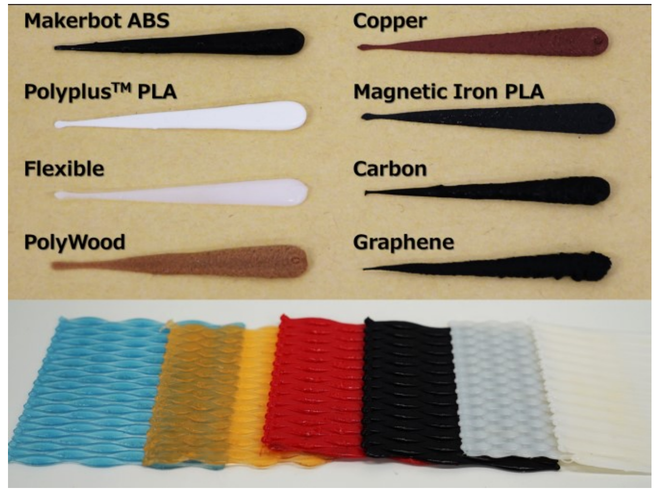

Figure 3. Application using various materials (top). We created a tactile sheet using PLA and flexible material (bottom).

Figure 4. Laser-cutting (left). Cutting out a sheet for a coaster (center) and watch strap (right).

a tactile sheet (Figure 3, bottom). The size of the sheet is freely adjustable according to the parameters used. NJB-200 has a 200 × 200-mm build platform, and we confirmed that our technique can be applied to every size. Note that the largest sheet (200 × 200 mm) takes two hours to print.

Application These printed sheets can be easily cut using scissors or a laser cutter (Figure 4, left). By cutting as required, we can utilize these sheets to assist with daily needs. For example, a sheet printed with flexible filament can be used as a coaster (Figure 4, center). This printed coaster is not only cut into a round shape to fit glasses, but also provides an antiskid function. This sheet can be also attached to existing objects. We attached it to a watch strap to change the feeling when touched into something resembling alligator hide (Figure 4, right).

CONCLUSION

We presented a technique that controls the thickness of objects being printed, and showed example objects and their usage. Like all printing techniques, our idea has limitations. The thickness in our technique depends on the performance of the 3D printer and the characteristics of the material. Although we showed that several materials can be used, it is necessary to analyze each factor in further detail. We will also investigate the features of objects printed using this technique (e.g., printing tactile cues).

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