3D Printed Fabric: Techniques for Design and 3D Weaving Programmable Textiles

Haruki Takahashi
Meiji University
Tokyo, Japan
haruki@meiji.ac.jp

Jeeeun Kim
Texas A&M University
College Station, Texas
jeeeun.kim@tamu.edu

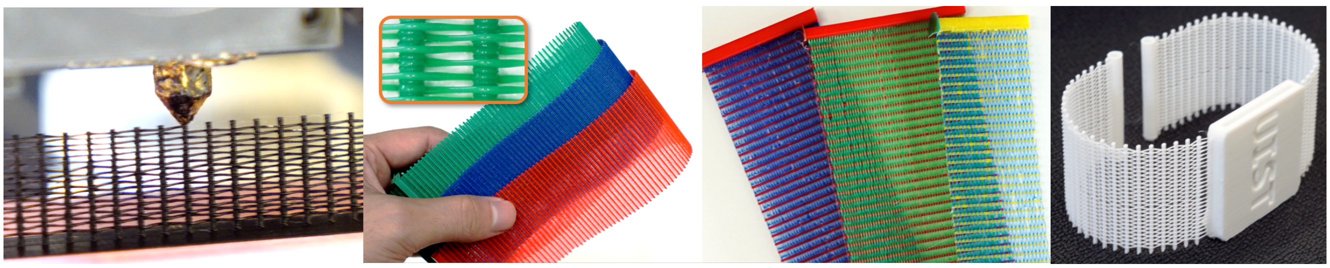

Figure 1. 3D printed fabric. Our technique can fabricate a textile that is woven using the movements of the nozzle of an FDM 3D printer.

ABSTRACT

We present a technique for fabricating soft and flexible textiles using a consumer grade fused deposition modeling (FDM) 3D printer. By controlling the movement of the print header, the FDM alternately weaves the stringing fibers across a row of pillars. Owing to the structure of the fibers, which supports and strengthens the pillars from each side, a 3D printer can print a thin sheet of fabric in an upright position while the fibers are being woven. In addition, this technique enables users to employ materials with various colors and/or properties when designing a pattern, and to prototype an interactive object using a variety of off-the-shelf materials such as a conductive filament. We also describe a technique for weaving textiles and introduce a list of parameters that enable users to design their own textile variations. Finally, we demonstrate examples showing the feasibility of our approach as well as numerous applications integrating printed textiles in a custom object design.

CCS Concepts

•Human-centered computing → Human computer interaction (HCI);

Author Keywords

Digital fabrication; 3D printing; fused deposition modeling; 3D printed textile; printing technique.

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INTRODUCTION

Recent advancements in additive manufacturing have enabled users to accurately fabricate 3D objects at low cost. The variety of choices of materials used in fused deposition modeling (FDM) for 3D printing, such as rigid plastic, flexible elastomers, and conductive materials, have enabled users to fabricate their own interactive objects [23, 24]. Furthermore, investigations into the FDM printing parameters (e.g., header's movement speed, extrusion amount, and extrusion height) have extended the capability of 3D printers, empowering users to create objects with hair [12] and fluffy textures [27] in addition to solid 3D objects without the need for any hardware innovations. In the field of human-computer interaction, fabric has been one of the promising materials used to create soft objects and presents interesting properties for the fabrication of everyday interactive objects [17, 20]. Fabric adds important properties, such as stretchability, breathability, and flexibility, to a solid object, which are difficult to achieve using rigid materials (e.g., ABS, PLA). Inspired by the use of fabric, researchers and artists have attempted to create 3D printable textiles and clothing through the assembly of small 3D printed pieces, similar to *chainmail*.

We present a new 3D printing technique that can fabricate a soft textile using a conventional FDM 3D printer and a rigid material (Figure 1). Our idea applies and extends the *3D printed hair* technique [12], adjusting the standard movement of a printer, and lengthening tiny bits of extruded materials (i.e., pulling the melted material by quickly moving the head away) to achieve a *stringing* effect. By controlling the movement of the nozzle within a row of pillars, a printer head alternately weaves 3D printed fibers using thin pillars. Unlike chainmail and 3D printed flexible sheets [5, 26], our textile is "woven" which is constructed by warps and wefts. Although a weft-knitted structure can be 3D printed, this type of complex structure requires an expensive printing method such as selective laser sintering or the use of a removable support material [1, 14]. Thus, our technique enables users to weave a variety of materials with a wide array of weaving patterns using a consumer grade 3D printer (Table 1). Because our technique does not print a weft in a layer-by-layer manner, a curved shape planned using a design tool can retain its original form and remain fixed when printed. We describe in detail our empirical experiments demonstrating how to weave a rigid plastic material using a 3D printer and provide a list of parameters that allows users to design their own programmable textiles. To discuss the feasibility and reproducibility of our technique, we also demonstrate the ability of our system to generate a Gcode from different geometries and selective parameters, and demonstrate its application.

RELATED WORK

Related studies on our technique span across the field of digital fabrication, particularly printing techniques for textile fabrication and the use of fabric in the printing interactive objects.

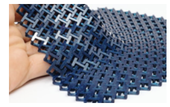
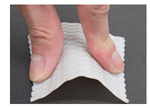
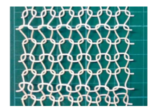
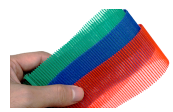
3D Printing Parameters and Control Techniques

Gcode is a series of commands used to control printer hardware mechanisms, e.g., the header movement, amount of extrusion, and temperature, which affect the shaping of an object. Researchers have used Gcode to control 3D printers, exploring new expressions rather than accumulating an object layer by layer [21]. 3D Printed hair [12] fabricates fine fibers by exploiting the stringing phenomenon of molten plastic. WirePrint [15] is a system used to build physical wireframes to reduce the printing time by tweaking Gcode for the header, moving diagonally along the z-axis. By controlling the height of the nozzle and the amount of material extrusion, expressive textures can also be printed using FDM [27]. Dual-color mixing [18] and 3D hatching [11] are used to control the layering of two colored materials when designing the surface of an object. New 3D printing techniques have extended the capability of 3D printers, and offer a new area of usage [9]. Using our technique, a new application and prototyping that complement the current 3D printing design space have been developed.

Digital Fabrication of/using Soft Objects

Although stiffness and texture are important characteristics of textiles, they remain a challenge to fabricate using current FDM. Thus, researchers have created deformable objects consisting of microstructures [7, 16, 25]. Meanwhile, textile has become a promising material presenting the possibility of integrating its unique flexible and soft properties when fabricated or embedded into a rigid object. Rivera et al. explored the integration of 3D printing of rigid plastic using on-the-shelf fabric with the embedding of textiles to add various soft properties, such as the ability to roll up a case cover or create a translucent lamp shade [20]. A layered-fabric 3D printer [17] is a new hardware system that feeds a sheet of felt for the construction of a soft interactive object. Medley [2] helps users navigate a library of embeddable materials with their own mechanical properties, presenting an interactive design tool enabling their integration into 3D printing. Printing Teddy Bears [6] introduces a needled print header to feed and 3D print yarn onto felt. Further, the approach has been extended

Table 1. Comparison of textile printing techniques.

Technique	Fabrication & Properties
 Chainmail [3]	Consisting of tiny interlocked parts: flexible and customable according to the parts per unit. The structure tends to be rugged because of the size of each part.
 Printed sheet [26]	Printed using a flexible material on the bed of a printer. By controlling the nozzle, various patterns can be expressed. The bottom of the sheet becomes flat.
 Weft knit [1]	Printed with a knitted structure. To form a complex shape, an expensive printing method (e.g., SLS) or a removable support material is needed.
 Our technique	Woven using warps (layer by layer) and wefts (fiber): flexible in the direction of the weft. Various materials are used to form patterns with a fine structure. The shape remains in a fixed form.

to a regular header to conduct electro-spinning at high voltage for the printing of fine grain yarn using a regular PLA filament [19]. Our technique enables entire fabric sheets to be created in a manner similar to the weaving of real fabric. The 'weaving' pattern determines the metamaterial characteristics (i.e., bending at a certain angle, and retaining a pre-defined curvature, which is similar to a shape-memory material).

Textiles as Material

Among designers and artists, there have been many attempts to explore the possibility of fabricating textile using 3D printed chainmail. Danit Peleg, a fashion designer, designs clothes made from printed textiles and has showcased various possibilities of 3D printed fashion[1]. Masaharu Ono, a Japanese artist, designs 3D printed clothes called *Amimono* fabricated using thermoplastic polyurethane[2]. In the domain of material science, Melnikova et al. explored various textile-based structures, and printed a weft-knitted structure using an FDM [14]. Beecroft printed a weft-knitted structure using an SLS 3D printer with nylon powder, and demonstrated its flexibility [1]. Combining 3D printing with a traditional fabric made with soft yarn is a popular area of exploration [4, 10, 13, 22]. With this design, soft fabrics are used as a substance for 3D printing to allow properties such as the flexibility and tensile strength to be applied. Although the precision of recent 3D printers and the quality of 3D printed objects have gradually improved since these innovative experiments were first conducted, the 3D printing of fabric remains a challenge. Designers rely on expensive 3D printers such as an SLS or need to understand the basics of the chainmail fabrication. Because chainmail consists of repeated tiny rigid units, the characteristics of such units and how they are chained dominate all physical traits of the textile (see Table 1).

[1] https://danitpeleg.com/
[2] http://free-d.net/

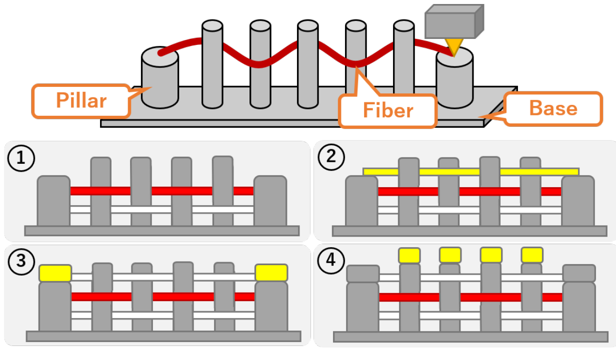


Figure 2. Our technique controls the height of the pillars and the order of printing to weave a fiber across the structures.

3D PRINTED FABRIC

Herein, we introduce the techniques for 3D printing a programmable textile. We used Creality3D CR-10S[3], a commercial FDM 3D printer, with the most common 0.4-mm-diameter nozzle and a 300 × 300 × 400 mm printing area. Several types of PLA, including Polymaker PolyPlus and PolyMax series, were tested. Although the brands of FDM printers and materials are diverse in the market, the basic settings and steps described herein serve as a baseline of the technique.

Weaving Fiber

Figure 2 depicts the structure of a printed textile and the printing order. The textile consists of three parts: a base (can be removed afterward), pillars (in the z-axis), and fibers (in the xy-axis). A base supports and upholds the entire structure while adhering it to the bed, similar to a brim. Pillars are equivalent to a *warp* in which header movements with a fiber extrusion across the pillars correspond to the *weft* applied in traditional looming. The two pillars at both ends are printed more thickly to firmly fix the endpoint of the fiber. We name the pillars at both ends the "outermost pillars" for later reference.

To weave fibers that are formed by extruded strands, we control the order of the printing rather than printing everything in one layer concurrently. First, a 3D printer prints all the pillars slightly higher than the outermost pillars (Figure 2-①). To avoid colliding with the pillars when printing the outermost pillars, we add a detour around the pillars and utilize the movement in the z-axis, which is also called a *Z hop*. Then, the nozzle starts to print a fiber from the top layer of the outermost pillar. The fiber is woven into a row of pillars alternately, by affixing the endpoint to the top layer of the other outermost pillar (Figure 2-②). After printing a fiber, the outermost pillars are extended (Figure 2-③), and the pillars of the next layer are then printed (Figure 2-④) to prepare the next-layer fiber weaving. The 3D printer iterates this process until completion. The fiber printing process (Figure 2-②) takes place in every two or three layers, to control the vertical density. The direction of fiber weaving is alternated in each layer (red and white lines in Figure 2).

Although the structure and printing order is relatively simple, there are many factors closely related to the FDM technique, which in turn, affect each other. For example, a thin pillar is easily broken during printing and the amount of material affects the thickness of a fiber. To explore the factors, we implemented a system that generates Gcode from the selective components: base, pillars, and fibers. The numbers reported below were obtained from empirical experiments using the system. Users can calibrate these with minimal changes to accommodate the unique machine/material characteristics, if necessary. During the printing experiments, this system was developed as a basis of the design systems that we will discuss in detail in a later section.

Components to Build Structure

We present the elements of the basic structure and parameters that need to be adjusted for stable printing.

Base - Because the base supports the entire structure in the z-axis, it is critical to print a significantly large base to uphold the pillars and fibers in place. A base does not necessarily need to be thick and can be printed as a thin plate with just a few layers, similar to *brim*. We currently design the base as a rounded rectangle, printed using two layers with 100% density and printed with the speed of 1,000-mm/min. After the printing, the base is removed manually.

Pillar - To print an exquisite sheet, the pillars must be printed as thinly as possible. We first set the printing speed to 500 mm/min, a slightly low value in order to print it carefully. It is fairly difficult to print a thin and high pillar in the z-direction if printed solely, because the movement of the nozzle may shake and twist the printed pillar as the layer proceeds. In our technique, however, the printed pillars and woven fibers can support each other in the structure as the fibers cross the pillars and hold them tight. As a result, we found that pillar diameters of approximately 0.8 mm can reach to a height of more than 300 mm. This pillar is printed with a contour path of a 0.4-mm-diameter cylinder. Because our 3D printer has a 0.4-mm-diameter nozzle, the extruded material swells slightly around the nozzle. To avoid a collision between the nozzle and pillars while printing, the interval between the pillars must be greater than the distance that allows the nozzle to pass through the spaces between pillars. Approximately 2.4 mm intervals from the center of the pillars was found to be appropriate. It is necessary to print the outermost pillars thicker and stronger, to fix the fibers to the end before the nozzle turns its direction to weave the next layer. Any geometrical shape is available for the outermost pillars as long as it is sufficiently strong to support its structural height. We printed a 3.0 × 6.0 mm rectangle to build the outermost pillar in a 0.2 mm layer height.

Fiber - To weave a fiber, we first applied the 3D printed hair technique [12], which pulls the extruded material by moving the nozzle away. We set the amplitude of the movement of the nozzle to 1.2 mm (from the center of a pillar to the farthest point of the fiber) according to the pillar interval. The flow rate is the most significant factor affecting the printing fiber by the amount of material extruded and the printing speed. When printing a long fiber, the area around the end of the fiber becomes thinner as the fixed amount of material exits in the nozzle channel, resulting in material running out while printing the fibers. Therefore, we set Gcode to extrude an additional amount of material when printing a fiber, by adjusting the

[3] https://www.creality3d.cn/

extrusion amount (E value). According to the amount of additional material applied, the thickness of the fiber differs, and we found that approximately 0.01–0.02 mm per 1-mm-length fiber is appropriate. The printing speed also affects thickness. Empirically, we found that a lower printing speed results in a constant thickness but takes longer to print; we set the printing speed to 500 mm/min, which achieved a good result in terms of quality and speed. If the fiber is too thin or the printing speed is too high, the fiber will snap during the printing process. In contrast, excessive material creates *drooping*. The vertical density of fibers is determined by the layer height and the count of skipped layers in between (Figure 2-②. We confirmed that a fiber can be printed once every two or three layers; if the layer height is 0.2 mm, the vertical interval for each fiber printing can be 0.4 or 0.6 mm.

Prevent Oozing - In general, to prevent oozing and a stringing of the material, an FDM printer retracts the material every step of movement. The process requires a certain distance of loaded filament to be retracted from the nozzle, and the retraction rate determines the motor speed to roll the filament back up. Depending on the type of material used, these values need to be slightly adjusted. For example, in Cura[4] slicer, an 6.5-mm retraction distance and 1,500-mm/min retraction speed are recommended as default. We set the retraction rate to 6.0 mm at 1,200 mm/min. We also slightly lowered the printing temperature to decrease oozing. For example, although Polymaker PolyMax filament recommends 190–230 °C, we used 185–195 °C.

Printing and Calibration

We confirmed that the suggested parameters are available with various types of commercial filaments and several FDM printers, including Creality3D CR-10S and Bonsai Lab[5] BS01+ 3D printer. Though it is unrealistic to test all the unique factors of FDM, users can start with the suggested values above with slight calibrations, according to the common troubleshooting tips (e.g., [28]). For example, if the fibers are sagging too loose such that they are not tightly attached to the pillars, the users will need to slightly lower the printing temperature. We recommend to first adjust the parameters corresponding to each component while printing a small textile. Some popular problems can be addressed with these trials and errors. If the users face further problems, we recommend validating environment-related factors, such as printing temperature, condition of the material and the global printing speed.

DESIGN SPACE FOR 3D PRINTING TEXTILES

In this section, we list a variety of parameters and their ranges associated with the printing process and their effects on the characteristics of printed textiles (Figure 3).

Length, Height, and Curvature - The maximum length and height of a fiber is constrained by the size of the bed. Our 3D printer has a 300 × 300 mm printing area, and because the outermost pillars are removed after printing, it limits the length to approximately 280 mm. We confirmed that our technique

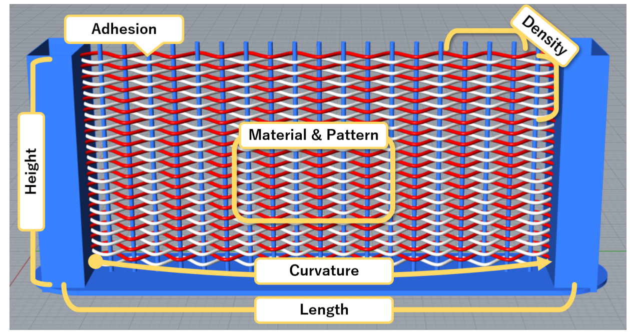


Figure 3. Design parameters of our technique. Each parameter provides a wide range of design space.

can fabricate textile up to 280 mm long and 300 mm wide, and that the fabrication of anything smaller will not be a problem. Although we assume that these dimensions are for a straight textile, a curved textile can also be made, in which case the maximum length becomes greater (see Figure 6).

Density - The density of printed fabric can be controlled in two ways: the interval between pillars, and the vertical density between horizontal fibers. By adjusting the frequency of the pillars, users can achieve different degrees of stiffness and transparency from a textile. A stripe pattern, such as a *moire*, can be obtained by fine-tuning the interval of the pillars.

Adhesion - Extruded molten plastic quickly cools down and solidifies in mid-air, becoming less adhesive to existing structures. We found that our technique can be used to control the adhesion by adjusting the printing speed and amplitude of the header movement in waves (i.e., the distance between the fiber and pillar). Therefore, the fiber can cling and be fixed to a pillar or unfastened and removed from the pillar as a part of the post processing. If users want to present a loose wave pattern for aesthetics instead of tightly coupled threads with pillars, the users can increase the amplitude of the waves allowing the materials to drizzle in mid-air. Although a fiber without a pillar is unstable, it memorizes the woven pattern.

Material - Users can integrate the material properties such as the color, flexibility, and conductivity. For example, by alternating two colored materials every several layers using a dual extruder, a striped pattern can be made on a sheet. However, it is difficult to form a fiber using a flexible and conductive filament in comparison with a regular PLA owing to their viscosity. Although these materials can be used as pillars, some calibrations (e.g., the amount of the material and the printing speed) are required to form a thin pillar.

Pattern - By controlling the movement of the nozzle, our technique can create various patterns on a textile surface. For example, to express a shifted stripe pattern, the nozzle weaves

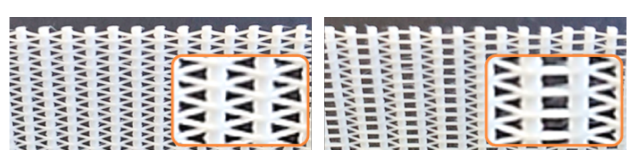


Figure 4. Weaving pattern, in which two or more pillars, and not just one, can be woven at the same time.

[4] https://ultimaker.com/en/products/ultimaker-cura-software

[5] https://www.bonsailab.asia/

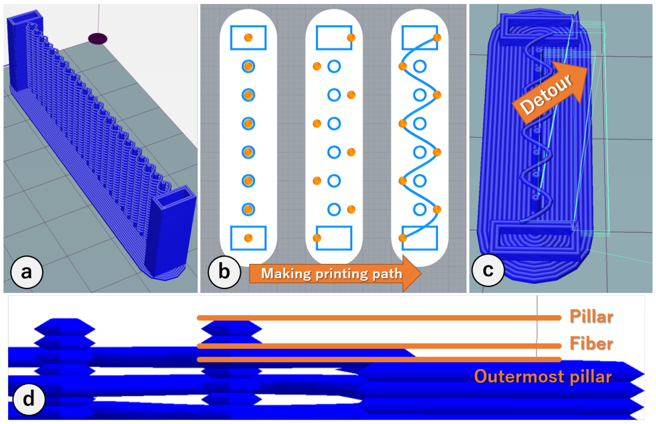


Figure 5. Generating a printing path for a textile: (a) Gcode preview. (b) Our system generating a path for printing fiber by interpolating the points obtained from the positions of the pillars. (c) To avoid colliding the nozzle with the printed structure, a path for creating a detour is added. (d) The heights of the inner pillars, the outermost pillar, and the fiber are also controlled to avoid a collision.

through two of the pillars at the same time rather than alternating single pillars (Figure 4). Similarly, binary images can be displayed on the surface by moving the nozzle to the front or back of the pillars (see Figure 7), allowing the weaving to present various stitch patterns on the surface.

DESIGN TOOL FOR PROGRAMMABLE TEXTILE

We implemented a system[6] that enables users to design textiles by exploring a number of parameters, exporting them as a Gcode (Figure 5a). Our system is implemented on Rhinoceros and Grasshopper[7], which is a visual programming language used to manipulate 3D geometries. Our technique presents a wide range of design spaces. We therefore extended our system to several different plugins.

Overview: From End User Design to Gcode Export

All extensions of our system share similar processes: (1) creating a geometry, (2) generating the printing paths, and (3) exporting to Gcode. First, according to the parameters given by the users and the parameters applied to the structural components, the system generates a base, pillars, and fibers, created by combining the components in Grasshopper, such as combining the *Circle* and *Extrude* components, to create a cylindrical pillar. To create a fiber, a list of center points of the pillars is moved outward in a zigzag pattern, and then interpolated with a line forming a curve (Figure 5b). Next, the system interprets the geometries to create the printing paths. Using the *Intersect* component and a series of xy planes aligned along the z-axis, the system first extracts the contours of the base and pillars. To create a thick shell, these contours are pushed inside based on the diameter of the nozzle. The system directly converts a fiber component into a printing path by dividing its curve at a certain interval (currently, 1 mm). To prevent colliding the nozzle with the printed parts, the paths used to create a detour are automatically added (Figure 5c). Finally, the system generates Gcode commands by splicing the printing paths. To weave fibers through the pillars, we adjust the height of each object (Figure 5d). Furthermore, we added a movement along the z-axis to waive collisions between objects at different heights. Before the nozzle moves to another component (e.g., from an outermost pillar to an inner pillar in the next layer), the height of the nozzle is set to the height of the inner pillar. When the nozzle moves between structures, the extruder retracts the material to keep it from oozing. The amount of material required to print the base and pillars is calculated using a known equation (e.g., [27]).

[6] https://haruki.xyz/printed_fabric
[7] https://www.grasshopper3d.com/

Programmable Structures

Herein, we introduce several types of design plugins. These independent systems share the same configuration and can be integrated with each other.

Straight Sheet

The simplest system is applied to control the design parameters of the simplest textile. All parameters are controlled by sliders or toggle buttons on Grasshopper. This process operates as the basis of constructing a sheet of fabric for a more advanced feature design. If users employ two types of material, the system builds a prime tower to wipe off the oozing material, and accordingly modifies Gcode based on the nozzle interval.

Curvature Sheets and 3D Solid Integration

Grasshopper scripts can import a 3D geometry from Rhinoceros, such as freely drawn lines and the contour of a square. In so doing, users can set the information regarding the shape of the textile. The system obtains a curve drawn in Rhinoceros and generates a curved textile along with imported lines. Similarly, a 3D solid mesh can also be imported into the system as a 3D object component. The system interprets an imported solid as a type of pillar and thus connects the edges of the fibers using a component that calculates the position of the closest edges from the endpoints of the fiber.

Patterns with a Binary Image

Our system also enables users to import a 2D image to populate a wide range of new weaving patterns. The system first converts the image into binary images using thresholding, and extracts the value of the black pixels using a grid. The grid is then divided by the interval of the pillars, and Gcode is generated to move the nozzle back and forth.

EXAMPLE AND APPLICATION

Basic example - Figure 1 shows basic examples designed using our system, which we designed using various parameters, particularly the *length*, *height*, and *material*. Many material colors, selected from Polymaker's PLA options, can be used by alternating the dual header nozzles, which allows two-colored fabric. The textile is approximately 260 mm wide and 50 mm high, and takes approximately 9 h and 11 m to print (Figure 1, second from the left). Given our constraints described above, the largest object we have printed is 270 $\times$ 270 mm. Users can bend, cut, or glue the textile to another object.

Multi-material - As briefly described, a dual header 3D printer can extend the capability of our technique with respect to the *material*. Figure 1 shows textiles woven using two colored materials for the pillars and fibers. We used a

Bonsai Lab BS01+ 3D printer, which provides a 150 × 130 mm printing area. Owing to the printing size constraints, we only demonstrated examples with a short length.

Integrating curved paths and 3D solid meshes - Our technique enables users to print a textile with various *curvatures* (Figure 6, left). We draw such curves in Rhinoceros to deform the textile and follow this curve at the bottom when printing pillars and fibers. We confirmed that a curved shape can be printed and that the shape is maintained, similar to a shape-memory material. However, fibers are slightly loosened around acutely angled pillars in a curve, because they cannot tightly hold a pillar (e.g., the inner fibers do not contact a pillar at this angle). By attaching a textile to a 3D solid, users can add flexibility to their design. As an example, users can design a smart watch cover using a traditional CAD tool and attach bands using our technique (Figure 6, right).

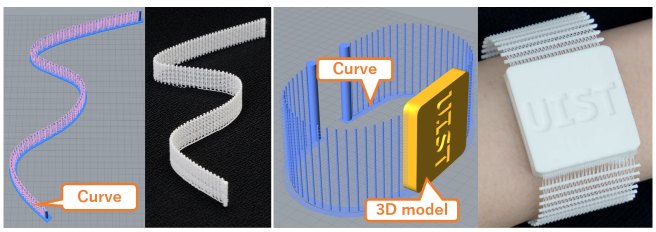


Figure 6. Textile printed in a curve and integrated with a 3D solid.

Pattern Generation - Controlling the *density* of the pillars enables users to design various textile patterns (Figure 7, top). We demonstrate two examples with stripes by controlling the thickness and interval of the pillars. Pillars with different thicknesses or densities enable users to present a shading on the textile. Controlling the weaving *patterns* empowers users to develop more complex patterns using a 2D input image. We demonstrated a textile created from binary images with a flower-like pattern and the UIST 2019 logo, respectively (Figure 7, bottom). However, because the pattern is created by moving the nozzle back and forth, an area where the same color continues cannot be woven and pillars cannot be sufficiently held. To achieve stability with the pattern, the weaving frequency used to hold the entire structure should be adjusted.

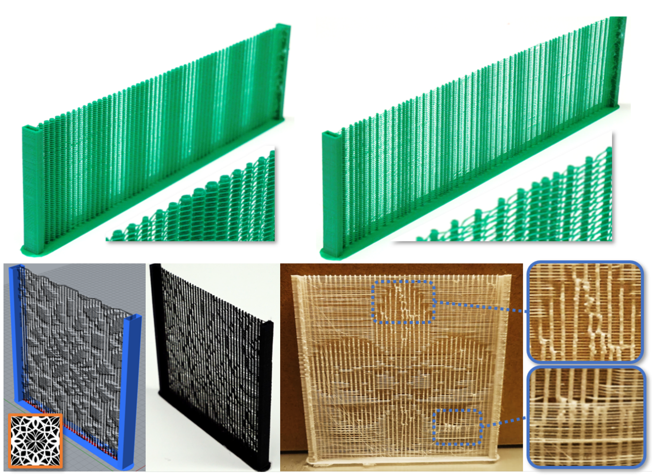


Figure 7. Design of textile pattern. We demonstrated two pattern types using the properties of the pillar and the weaving pattern.

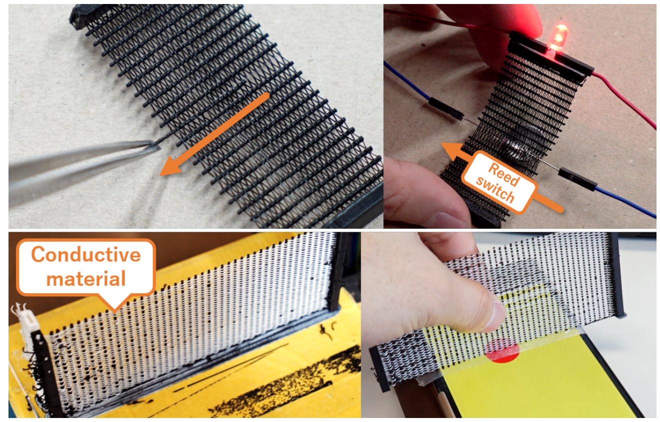


Figure 8. Interactive object integrated with electronics and printed using conductive ABS.

Interactive objects - Electronic components and various materials can be incorporated into the printing textiles. By lowering the *adhesion* of the fibers, a pillar can be detached from a complete textile for removal as a part of the post processing, allowing us to replace them with a reed switch (Figure 8, top). Combining digital fabrication and a craft technique (e.g., manually inserting existing materials) empowers users to prototype these interesting interactive objects using various materials that are unsuitable for low-cost 3D printing [9]. Textile printed with conductive materials enables users to make interactive objects with an integration of circuits and small electronics (Figure 8, bottom). We used a conductive ABS filament to print the pillars and a PLA filament for the 3D printed striped textile. We found that this object with a stripe [8] can transfer a touch interaction throughout, allowing the touch surface to be operated using the edge of the attached textile.

DISCUSSION

Herein, we discuss the structural property of a printed textile, the limitations of our work, and future works.

Preliminary evaluation

To understand the characteristics of a printed textile, we present preliminary evaluations on the structural properties. We printed textiles using the settings we mentioned in the section on 3D printed fabric.

Flexibility - Figure 9 shows a flexibility test using a textile. We investigated two bending directions by fixing one edge of

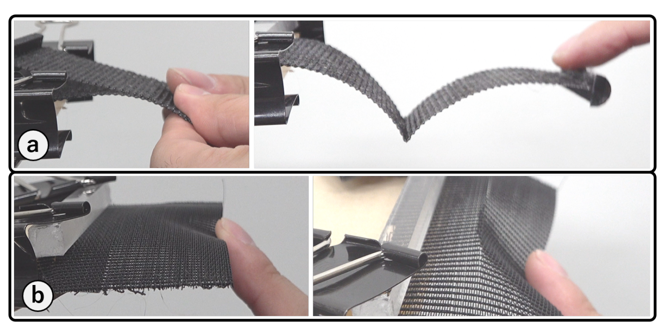


Figure 9. Preliminary evaluation of the flexibility. (a) Folding the textile in the weft direction and (b) bending it in the warp direction.

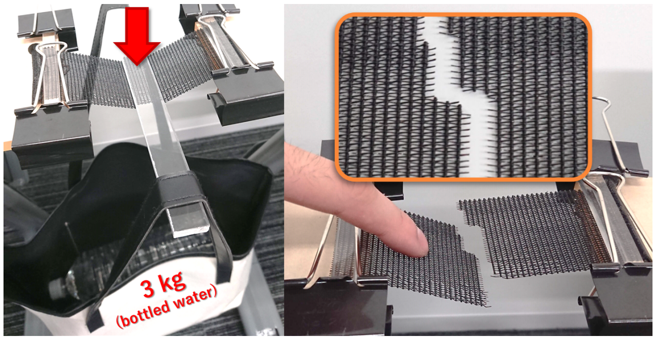


Figure 10. Preliminary evaluation of the strength.

the textile. Because the weft is made from a single fiber, the textile is flexible in the weft direction. Similar to a regular sheet of paper, the textile can be folded (Figure 9a). Although the textile is slightly flexible in the warp direction, it is easily broken into pieces by bending. Because a wrap is printed layer by layer, it is weak to forces in the shear direction (Figure 9b).

Strength - As shown in Figure 10, we hung a bag containing bottled water on a textile using a jig. The textile can hold approximately 3 kg, and starts to break at over 4 kg. The broken points are considered some pillars and a part of fibers where touches the pillar. We found that the printed textile has a sufficient load bearing capacity. The strength of a printed textile can be enhanced by thicker pillars and fibers, and users can print more durable textiles.

Limitations and Future work

As briefly introduced with 3D printed hair [12], our technique cannot employ materials in which a stringing effect does not occur. We found that TPU, a conductive, wood-like material has difficulty creating fibers owing to its out of bound viscosity. Nonetheless, as we showed through our interactive object example, such materials can be used to print pillars (rather than fibers) using a 3D printer with a dual header. As we showed in the preliminary evaluation, the degree of flexibility of the textile differs based on the direction, and can be broken if the textile is excessively bent in the direction in which the pillar is constructed, which is rigid.

We believe that our technique can be optimized based on the type of material, 3D printer, and parts. For example, using a finer extruder tip diameter of 0.1 or 0.2 mm, our technique makes it a lot easier to print delicate fibers. Although we only dealt with upright pillars, by shifting the layers while printing, curved pillars can be woven into a textile. Aligning the pillars in two dimensions also makes it possible to create 3D (like a stringing art) and double (a traditional weaving technique using multiple layers to express a complex pattern) weaved materials. We leave more constructive structural tests on further parameters affecting the characteristics of the textile to future studies.

CONCLUSION

We presented a new 3D printing technique for textile fabrication at low cost, using a consumer-grade FDM 3D printer. Given a variety of parameter choices, our technique enables weaving a thin fiber across a series of pillars within the design space of the fabricated textile. We introduced a system that enables end users to design various textiles by exploring different parameters. Exemplary applications demonstrate how our technique can be used in a real-world fabrication, allowing users to introduce thin threads as a new design medium for their 3D models. The proposed technique will expand the application domain of 3D printing, opening a new door for users to recast the use of printers in everyday design, not only for rigid objects but also for objects with soft textiles.

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