Chapter Title: CILLLIA: METHOD OF 3D PRINTING MICRO-PILLAR STRUCTURES ON SURFACES
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CILLLIA
METHOD OF 3D PRINTING MICRO-PILLAR STRUCTURES ON SURFACES

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Throughout nature, hair-like structures can be found on animals and plants on many different scales. Beyond ornamentation, hair provides warmth and aids in the sense of touch. Hair is also a natural responsive material that interfaces between the living organism and its environment by creating functionalities like adhesion, locomotion and sensing. Inspired by how hair achieves those properties with its unique high-aspect ratio structure, this project explores ways of digitally designing and fabricating hair structures on the surfaces of manmade objects. Material science and mechanical engineers have long been investigating various methods of fabricating hair-like structures[1,2]. In this paper, we present Cilllia, a digital fabrication method to create hair-like structures using stereolithographic (SLA) 3D printing.

The ability to 3D print hair-like structures would open up new possibilities for personal fabrication and interaction. We can quickly prototype objects with highly customised fine surface textures that have mechanical adhesion properties, or brushes with controllable stiffness and texture. A 3D printed figure can translate vibration into a controlled motion based on the hair geometry, and printed objects can now sense human touch direction and velocity. In this paper, we will focus on introducing the fabrication pipeline and the emerging mechanical adhesion property of the printed hair surface.

The 3D printing revolution

3D printing is rapidly expanding the possibilities for how physical objects are fabricated[3]. Its layer-by-layer fabrication process has tremendous potential to enable the fabrication of physical objects not previously possible. High resolution 3D printers have become increasingly affordable and widely available, enabling the fabrication of micron-scale structures. Cilllia is a bottom-up printing pipeline intended to fully utilise the capability of current high resolution photopolymer 3D printers to generate large amounts of fine hair on the surfaces of 3D objects. We introduce methods, algorithms and design tools for the fabrication of Cilllia and explore its capabilities for mechanical adhesion.

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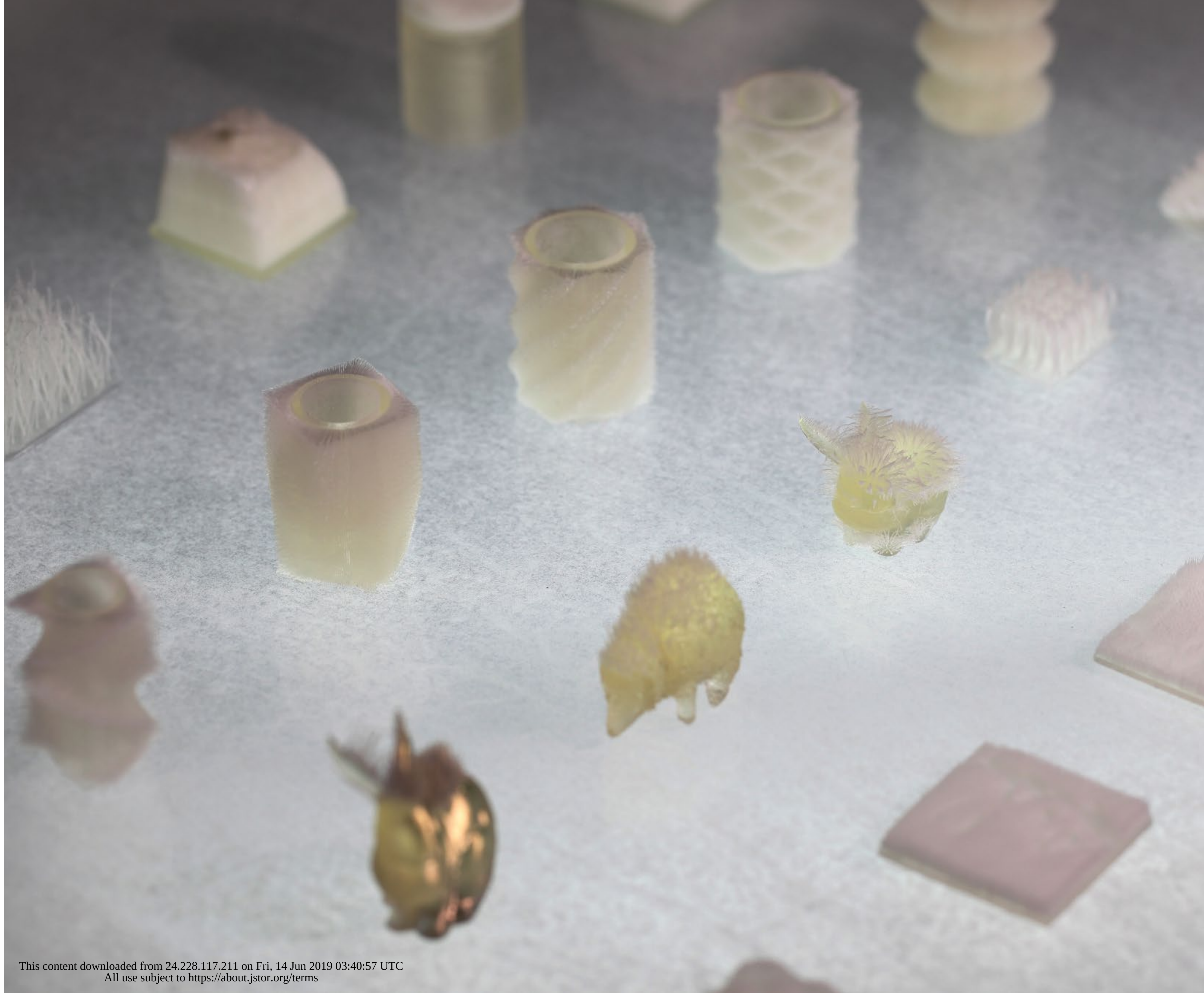

In this paper, the following contributions are presented:

1. A bottom-up approach for generating 3D printable micro-pillar structures.
2. A simple graphical interface that allows users to easily design hair structure.
3. Examples of encoding mechanical adhesion property into hair structures.

As high resolution 3D printers become increasingly available and affordable, we envision a future where the properties of physical materials, whether optical or mechanical, electrical or biological, can be encoded and decoded directly by users. This allows us to customise and fabricate interactive objects as needed.

The challenges of Cillla

Although the resolution of recent 3D printers has been improving, it is still considered impractical to directly print fine hair arrays on object surfaces. This is due to the lack of an efficient digital representation of CAD models with a fine surface texture[4]. Most of the current commercially available 3D printers use a layer-by-layer method to deposit/solidify materials into shapes that are designed in CAD. The process follows a top-down pipeline, in which users create digital 3D models, and then a programme slices the models into layers for the printer to print. In the field of computer graphics, the standard way to represent surface texture is through lofting bitmaps on the CAD model to create an optical illusion. These representations do not actually capture the three-dimensional structure. It is difficult and impractical to create many thousands of small hairs with real geometry using conventional CAD systems. The data for describing the total geometry become extremely large and rendering such complex structures can also be computationally expensive.

To overcome these challenges, the goal of the project is to bypass the modelling and slicing process of the 3D printing, and instead to directly generate machine-readable files that reconstruct hair-like structures.

3D printing hair-like structures

We introduce a bottom-up approach to 3D printing hair-like structures on both flat and curved surfaces. Our approach allows users to control the geometry of individual hairs, including aspects such as height, thickness and angle, as well as properties of the hair array, such as density and location. We then present three example applications to demonstrate the capabilities of our approach.

All the tests and examples shown in this paper, unless stated differently, are printed on a commercially available digital light processing (DLP) 3D printer (Autodesk Ember Printer). The DLP printer takes stacks of bitmap images from the CAD models and directly projects the image onto the liquid resin layer by layer. The printer has a feature resolution of 50µm on the X and Y axes, and 25µm on the Z axis. The build volume is 64 x 40 x 150mm. The print material is near UV light photopolymer.

Printing hair-like structures

The bottom-up 3D printing approach presented here allows one to design and fabricate hair-like structures without first making a 3D CAD model. The user directly generates printing layers that contain hair structure information for the 3D printer. The method can be viewed in three layers:

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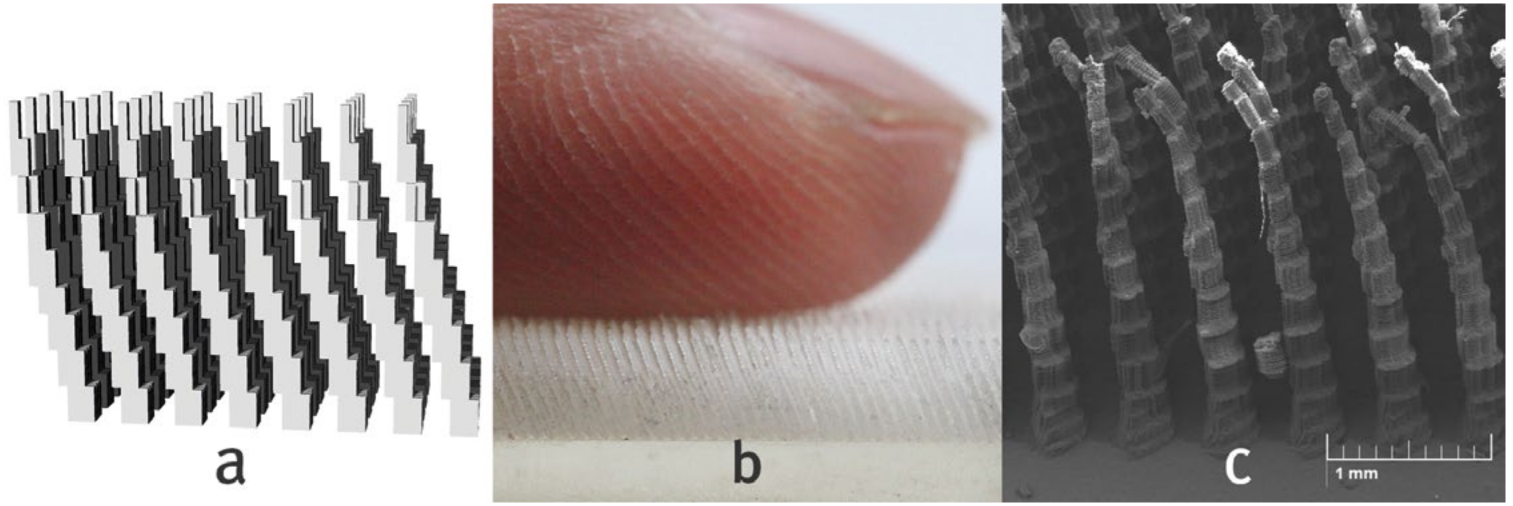

2. (a) Computer visualisation of printed hair; (b) close view of actual printed hair; (c) SEM photo of (b).

1. A single hair's geometry (1D): height, thickness, angle and profile.
2. Hair array on flat surfaces (2D): varying single hair geometry across the array on a 2D surface.
3. Hair array on curved surfaces (3D): generating hair array on arbitrary curved surfaces.

Single hair geometry

Compared to other surfaces textures, such as the wrinkle, hair is simple to describe mathematically. It usually comprises a high-aspect ratio cone that is vertical/angled to the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore we need to find a way to construct a model that could approximate the geometry of a cone. We set the base of a pillar to be a matrix of array (e.g. 3 x 3 pixels). As the layer increases, the pixels linearly reduce in a spiral stairs manner, leaving the top layer with just one pixel. This method gives us the highest resolution control of the printed cone shape. We can also add acceleration to the base pixel, reducing velocity to create hair with a different profile.

For tilting the hair to a certain angle, we can offset the pixel group in the X or Y direction every few layers. As the printer has the double resolution on the Z axis compared to the X and Y axis (25µm vs. 50µm), the relationship of tilted angle and layer is:

$$\tan\theta = (L/2) \times P$$

where L is the number of layers and P is the number of offsetting pixels. We successfully printed a series of sample surfaces with oriented hair. Fig. 2 shows that our printed geometry matches the computer visualisation.

Users can easily change the parameters of the hair geometry through a graphical user interface that we designed. It visualises the hair structures as well as generating bitmaps for printing.

We can also generate curved hair by offsetting the pixel group in a spiral layer by layer.

Hair array on flat surfaces

The ability to individually control hair geometry can be applied to thousands of hairs across a flat surface. In order to do this quickly, we use a colour mapping method to make an RGB bitmap in Photoshop, then turn it into a hair array. The values of the R, G and B of each pixel correspond to one parameter of hair geometry. The algorithm checks the bitmap every few pixels to create a new hair based on the pixel's colour. One can therefore easily vary the density of the hair by changing how frequently the bitmap is checked.

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3. Successful printed hair arrays on curved surfaces.

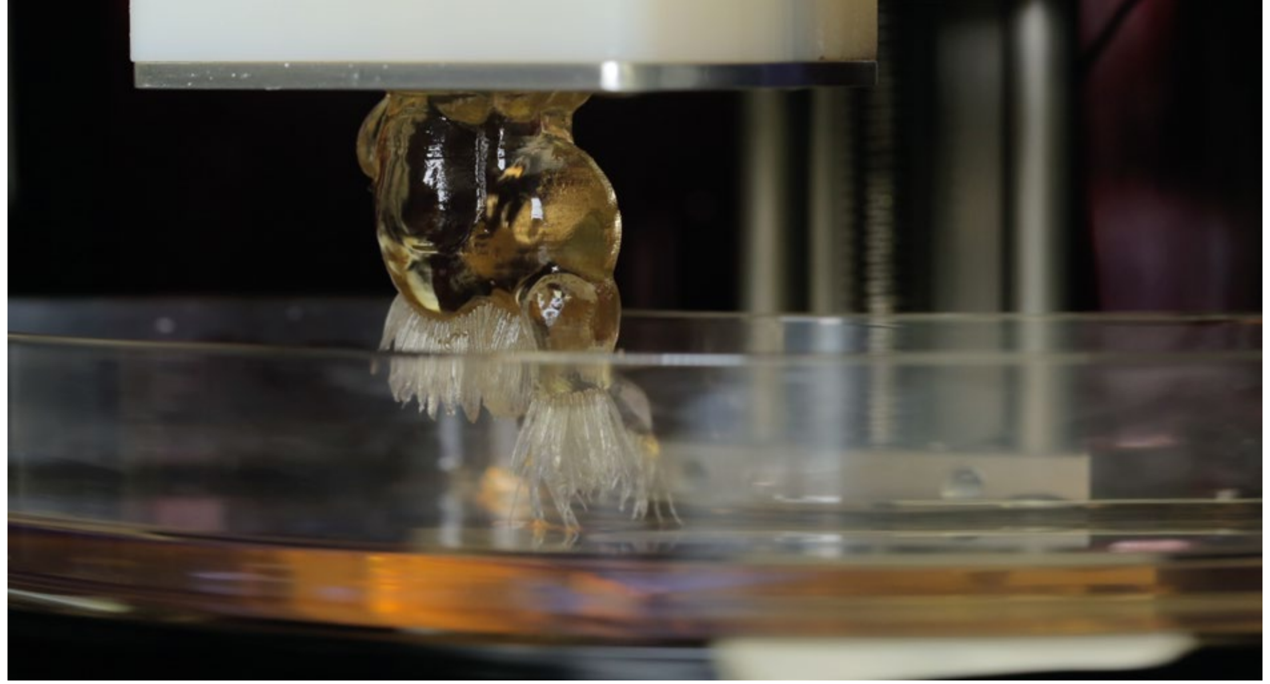
Based on our experience, height and angle are the most common parameters that need to be varied frequently. We therefore map the R-value to the angle of the X axis, the G-value to the angle of the Y axis and the B-value to the height of the hair. We use this method to create the conveyor panels in the later section. In the future, we plan to develop a more general approach to encode hair geometry information into one bitmap image, where other parameters such as profile and thickness can be included as well.

Hair array on curved surfaces

In order to apply the presented techniques to a variety of models, it is desirable to print hair on an arbitrary curved surface. To do that, we developed a hybrid method, where users create the curved surface in CAD software, then generate bitmaps that contains pixels of hair array.

To do this, we first import the STL file and position it in the correct printing position. We then find the centroid location of each triangle on the mesh and shoot a ray along the direction of the triangle's normal. A plane moves along the Z axis to intersect with the mesh to create bitmaps of the CAD model, and to intersect with the rays to draw pixels for the hair. In this way, we created bitmaps that contain both CAD model and hair array information. This method allows us to apply the control of hair geometry while slicing as well. However, the generated hair array is highly dependent

1. A collection of 3D printed hair-like structures on flat and curved surfaces. The voxel-based printing approach allows one to define each hair's geometry. Image: Jifei Ou, MIT Media Lab.



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4. A DLP printer is used for hair printing. Image: Jifei Ou, MIT Media Lab.

on the distribution and amount of the triangles. For the examples in this paper, we try to use meshes that have dense and evenly distributed triangles. One can use publicly available online tools (e.g. Meshlab) to create more uniform models. We should also notice that the 3D printer allows only 60° of overhang, so rays beyond that range are ignored. There might also be parts of the hair that penetrate the nearby surface if the surface is curved inwards. We can eliminate this by reducing the hair length correspondingly (Fig. 3).

There are three advantages when directly generating bitmaps of hair structures:

1. By manipulating a single pixel, we can control aspects of a single hair's geometry, such as height, thickness and angle, with a precision of 50μm.
2. Without a CAD model of the hair and slicing process, it becomes possible to print a high density hair array. In our test, we successfully printed 20,000 strands of hair on a 30 x 60mm flat surface.
3. Hair array can 'grow' on any arbitrary CAD model while the model is being sliced.

Printing with laser beam-based SLA

We also experimented with the layer-by-layer method on a laser beam-based SLA printer (Form1+). In the experiment, we directly manipulate the exposure time and the moving path of the laser beam to create an array of laser 'dots' for polymerising the liquid resin. We move the laser beam to the spot where we would like to have hair structure and turn on the laser for two milliseconds, then move to the next spot and turn it on for another two milliseconds. Based on our experiment, two milliseconds is the minimum exposure time one needs to fully polymerise the resin. It produces a dot with a 100μm diameter. To increase the size, one can increase the exposure time. However, we discovered that as one increases the exposure time, the polymerised dot forms into a long oval instead of a circle shape. This is due to the shape distortion of the laser beam. Although the Form1+ has a larger build platform and potentially can be useful for more applications, we decided to use the Ember printer, as it produces more uniform results.

Applications for designers

To show the capability of our printing method, we created three types of possible application for designers.

Objects with fine surface textures

As we can generate hair on curved surfaces, we can now 3D print animal figures with such features. We can also vary the thickness of the hair to create jewelry pieces with controllable stiffness (Fig. 5).

Customised brushes

We can also directly 3D print brushes with customised textures and different densities. With the colour mapping method, one could create a more complex shape of brush for increased and varied artistic expression. In our example, all brushes are 30mm in diameter. The length and density vary based on the input bitmap.

Mechanical adhesion

One interesting phenomenon we found during our exploration is that two panels with dense hair can tightly stick to each other when their hair is pressed together. This is due to the large amount of contact surface on the hair that creates friction. To demonstrate this, we printed several hair panels (40 x 40mm) and glued them into boxes. These boxes can be easily attached to each other. In order to keep the hairs on two panels fully in touch with each other, the gaps between the hairs must have the same size as the diameter of the hair base. In our example, the hair base and the gap are both four pixels (200μm).

We tested the strength of the adhesion in relation to the tilting angle of the printed hair. In our experiment, a pair of hair panels (30 x 30mm) were glued onto a solid truncated pyramid (30 x 30 x 30mm). We pushed the hair surfaces against each other and measured the force that was needed to pull them apart. Our test shows that as the tilting angle of the hair increases, the adhesion force rises as well.

Successful fabrication of customised hair-like structures

To summarise, we present a method of 3D printing hair-like structures on both flat and curved surfaces. This allows a user to design and fabricate hair geometry at the resolution of 50μm. We built a software platform to let one quickly define a hair's angle, thickness, density and height. The ability to fabricate customised hair-like structures not only expands the library of 3D printable shapes, but also enables us to design surfaces with mechanical adhesion properties.

While we demonstrated methods and a possible design space for 3D printed micro-pillar structures, we are aware that the technique is very much limited by the physical constraints of current SLA 3D printers. For example, if we had to create an arbitrarily shaped object fully covered by hair, we would have to split the object so that the curvature of the surface could still be printed without a supporting structure. The printable materials are also limited in terms of colour and stiffness. Our current algorithm for generating hair on curved surfaces is also highly dependent on the amount and distribution of the triangles of the CAD model. This means that to print high quality hair requires either a clean mesh model or a preprocessing step for the model. In the future, we will add re-mesh functions to our software platform to control hair distribution. It would also be very interesting to test if tilted hair is mechanically weaker than straight hair, as there is less contact area for each layer of the voxel.

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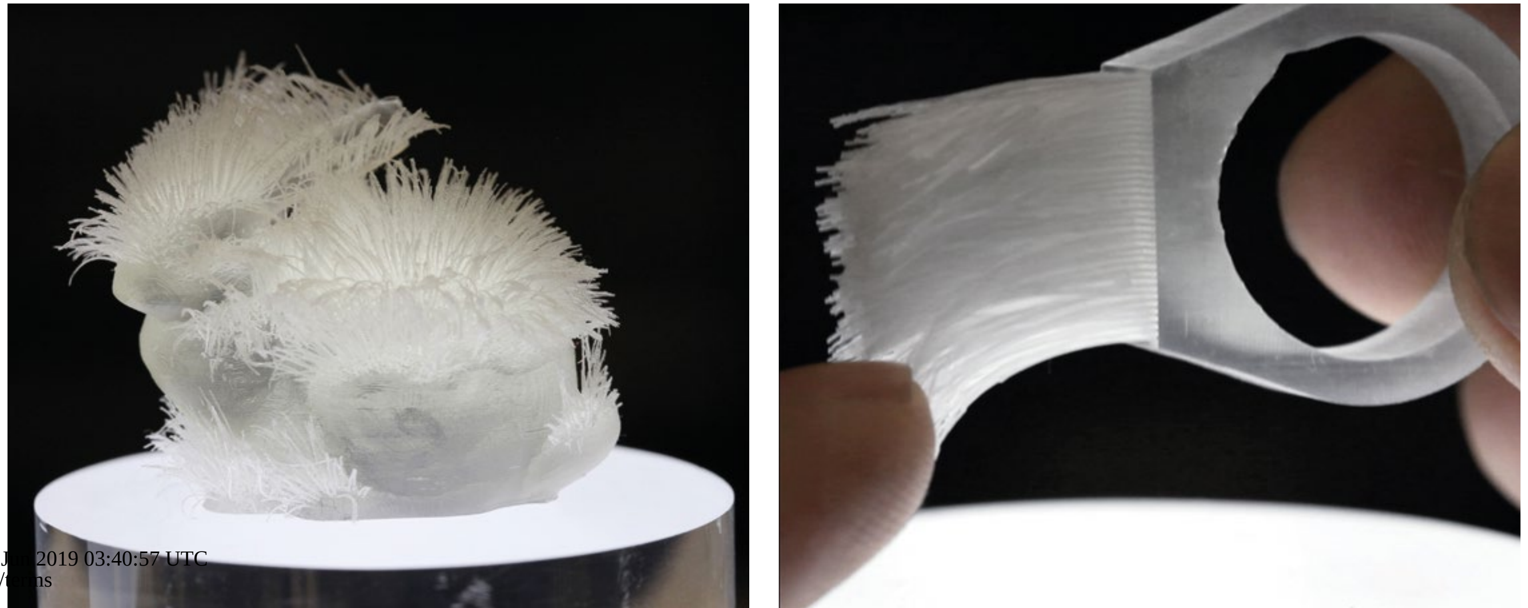

5. Printed figures with fine surface texture.

Notes

1. Amato, L., Keller, S.S., Heiskanen, A., Dimaki, M., Emnéus, J., Boisen, A. and Tenje, M., 2012, 'Fabrication of High-Aspect Ratio SU-8 Micropillar Arrays', *Microelectronic Engineering*, Vol. 98, ISSN 0167-9317, p.483-487.
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