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A Semi-skilled Fabrication Approach of Shape-Changing Interfaces through Fused Filament Fabrication

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Abstract. The common additive manufacturing techniques like fused filament fabrication (FFF) routinely produce physical, rigid structures. But using this production technique for manufacturing flexible structures with high-end materials such as thermoplastic polyurethane (TPU) is more difficult. Because of its difficulty, the fabrication of these structures requires higher-end machinery, time-intensive fabrication, and skilled users. Therefore, we focus on the malleable dynamics of a rigid thermoplastics with mid-range FFF technology to expand the design-space of shape-changing interfaces and propose a fabrication approach for it. As a result, the intended user, for example a creative designer, can also integrate shape-changing interfaces of rigid thermoplastics in their designs, much sooner than if constrained by an FFF printing platform. In a first phase, we experiment with different materials through an iterative design-based process. In a second phase, we perform an explorative design-case study to test the material's flexibility and the fabrication approach. The research is concluded with an approach proposal, discussion and future work.

Keyword: Fused filament fabrication · Shape-changing interfaces · 3D printing · Additive manufacturing · Interaction design · Design experience

1 Introduction

We aim to investigate the fused filament fabrication (FFF) technology of rigid thermoplastics for shape-changing interfaces through an iteration-based study. FFF techniques facilitate the production of complex design artefacts with unique aesthetics and functional properties [1]. In the field of shape-changing systems, the concept of 4D printing is also discussed [2]. It permits 3D printed structures to include a dimension of time. As a result, it can change their form under the influence of environmental factors such as temperature, illumination, pressure etc. [2]. But 3D printed materials and structures mostly lack mechanical properties for 4D printing. To overcome these limitations, researchers

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have investigated the flexible capabilities of FFF, for example with printing layers as thinly as possible. The garments designed by the Iris van Herpen atelier, Catherine Wales and Michael Smidt in collaboration with architect Frances Bitonti are examples hereof which demonstrate the flexible capabilities of FFF technology for computational design [2, 3]. The textile properties of these woven structures with FFF printed structures have already been determined [3–5]. Fabricating these garments require specific skills, a time-intensive production process and a considerable amount of manual labor. The Foliage Dress by Iris van Herpen for the Paris Fashion Week 2018 took 260 h to 3D print, only for the parts, excluding the assembly [1, 6]. Therefore, we developed and propose a semi-skilled fabrication approach based on primarily using the malleable dynamics of FFF technology for printing upon woven fabrics to expand the design space of shape-changing interfaces for the creative intended user.

We try make this technique accessible for the early majority of the intended users who own mid-range 3D printers and could fabricate the proposed hybrid material with low effort. As an opportunity, the hybrid material will consist of rigid thermoplastics conventional materials to increase its flexibility and its appeal. In this study, we demonstrate the following. In a first phase, we investigated the malleable dynamics, materials and fabrication opportunities of FFF by performing an iterative prototyping process in five phases. After the iteration process, a fabrication approach is proposed with a prototyped hybrid material as a result. In a second phase, we conducted an explorative design case study to demonstrate the potential of this hybrid material.

2 Methods

An iterative-design process suited this type of research best, due to the trial-and-error approach and low-end to high-end prototyping of the hybrid material. In total, five iterations were performed. Each iteration focuses on a different aspect. Several tools and machinery were used to cut or pre-fabricate each material. To speed up prototyping with each iteration, fabrication was initially done using handheld tools, but once the design prototype was finalised, we switched to using machinery such as laser cutters and 3D printers. The first iterations were performed without FFF printing to ensure quick prototyping. Wooden veneer was used as replacement material for the PLA for the FFF tiles in these iterations.

2.1 Experimental

The materials in all five iterations can be divided in three main categories: fabrics, wood, and thermoplastics. A transparent, cellulose nitrate-based adhesive, applicable to all wood-based materials and most types of plastic, is not included. Cotton fabric and nylon tulle were used in the fabric category. They were all cut manually using scissors. Three types of wooden veneer were included in the wood category: oak, bamboo and meranti, each with a thickness of 1 mm, cut with a laser cutter. In the final category, only the thermoplastic polylactic acid (PLA) is used as filament to 3D print structures. The 3D models of the structures were designed with CAD software, namely Solidworks 2019. Once modelled, the structures were exported as Standard Template Library (STL) files and imported in slicer software. The slicer software used is PrusaSlicer, because one of the mid-range FFF printer, here the Prusa MK3s (Prusa Research, Czechia). The second mid-range FFF printers was the Makerbot Replicator 2 (United States). The parameters of both 3D printers were the extruder temperature, set at 215 °C, and the printing bed temperature, set at 60 °C.

2.2 Iterative Design Solutions

To make the hybrid material as applicable as possible for the case study described in Sect. 3, the test set-up resembles a cylindrical shape with the same dimensions. The fabrics, which are fully flexible, form the base of the hybrid material to which either the wooden or PLA tiles are glued. The design of the tiles, formerly 3D structures, determines the foldability and the look of a corrugated effect. This design is based on earlier research on foldable structures, such as origami, the art of making objects by folding sheets of paper into shapes, miniature origami robots and tessellation mathematics [7, 8]. The foldability parameter in this experiment is measured as the Z-length reduction, as seen in Fig. 1. As objective for the iterations, the Z-length reduction must be at least 50% compared to the original Z-length.

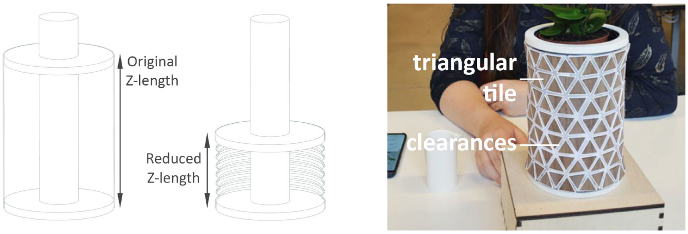

Fig. 1. Z-length reduction – tessellated triangular design

We decided on a triangular tessellation for following reasons. Firstly, the two strongest shapes possible are a circle, on the first place, and a triangle, on the second place. However, the advantage of a triangle is that the folding lines, seen in origami, are already defined. Secondly, a triangle possesses nine degrees of freedom; six corner translations and three corner normal rotations. With each corner added, rectangles, pentagons, hexagons etc., the number of degrees of freedom increases. And thirdly, as a linear force is applied to stretch or compress the hybrid material in the Z-direction, all force is distributed on the tiles down the sides to the triangular joints, similar to principles in truss design. For instance, when using a rectangular tessellation, the linear force could also be distributed across the diagonals, resulting in in-plane bending. In-plane bending occurs even more frequent when polygons with more corners are used.

Iteration One. The first iteration focuses on the exploration of the low-end materials, cotton fabric and oak veneer. The hybrid material resulting from this iteration is used as a baseline. ***Design process:*** The size of one triangular tile was set at 20 mm to 17 mm. Seven rows and five columns of these tiles results in a size of 100 mm to 119 mm, the size of the cotton fabric as well. ***Prototype:*** The tiles were laser cut out of oak, meranti and bamboo veneer. Doing so, an intricate design led to a more appealing look. Within 2 min, 100 tiles could be laser cut, called the cut-to-tile ratio further on. The tiles, 63 in total, were glued on the cotton fabric, one by one. This assembly took one hour. The clearance between the tiles, as can be seen in Fig. 1, was 2 mm. ***Experiment:*** The targeted Z-length reduction was 0.34 equal to 34% (x).

$$(\text{Original Z-length} - \text{Z-length reduction})/\text{Original Z-length} = \text{x}. \tag{1}$$

Analysis: The small tiles and large clearances set a Z-length reduction baseline of 34%. However, the assembly time took too long. Using three wooden veneer types created a more appealing look but will only be an option as the user sees fit.

Iteration Two. Here, a reduction of the assembly time is most pressing. This is more specifically done by adjusting the laser cutting process. ***Design process:*** The width of the clearance increased, hoping to improve the Z-length reduction. Seven rows and six columns of oak veneer tiles changed the hybrid material's size from 120 mm to 123 mm. The tiles, however, were still connected after cutting due to nodes between them. From this point on, the triangular tile and hybrid material sizes remain the same in each iteration. ***Prototype:*** The tiles were laser cut in oak veneer. The cut-to-tile ratio increased slightly. The entire piece was glued on the cotton fabric and each node was broken. This assembly took 15 min, a reduction by 300% compared to iteration one. ***Experiment:*** The targeted Z-length reduction was only 0.11 equal to 11%. ***Analysis*****:** Introducing nodes reduced the assembly, but at the cost of the Z-length reduction, because it prevented the foldability. The adhesive also did not adhere to all tiles. Nodes are therefore not the solution.

Iteration Three. Although cotton fabric is flexible, it proved to be too stiff for a hybrid material. Therefore, it is replaced with nylon tulle and 3D printed tiles. Inspiration for this technique can be found in the work of Iris van Herpen [3]. The goal is to decrease labor and assembly time by snap fitting the oak veneer tiles without adhesive. ***Design process:*** The design of the 3D printed tile consisted of a full printed base and a rim acting as a holder for the oak veneer tiles. ***Prototype:*** The nylon tulle was attached to the acrylic build plate using paper tape. The tiles were printed directly on the nylon tulle. The PLA melted around the nylon mesh threads, encasing it. The printing time was 124 min at a 0.1 mm layer thickness. The oak veneer tiles were laser cut and fitted in place. The assembly took six minutes. ***Experiment:*** The targeted Z-length reduction was 0.23 equal to 23%. ***Analysis*****:** Using FFF printing, the positioning of the triangular tiles and the clearances were much more accurate. The triangular tiles did not adhere good enough to the nylon tulle. The absence of adhesive and too little friction caused some oak veneer tiles to fall out the triangular tiles (Fig. 2).

Fig. 2. Iteration Four: Experiment and top view hybrid material

Iteration Four. The triangular tiles must adhere better to the nylon tulle by increasing the friction between the triangular tiles and the oak veneer tiles. ***Design process:*** The center of 3D printed tile was removed in the design to decrease printing time. The rim was still 1 mm wide, but had a smaller tolerance between the rim and the oak veneer tile. ***Prototype:*** A new mid-range printer was used, a Prusa MK3s. As for the fabrication process, firstly, the bases of the triangular pieces were 3D printed. Secondly, midway, the print was paused and the nylon tulle was clamped on the metal build plate using eight magnets. Thirdly, the rim was 3D printed on top, adhering to the bases below with the nylon tulle in between. The printing time was 89 min. The oak veneer tiles were laser cut and fitted in place. The assembly took six minutes. ***Experiment:*** The targeted Z-length reduction was 0.34 equal to 34%. ***Analysis*****:** The triangular tiles adhered much better to the nylon, as can be seen below. Some of oak veneer tiles however did still fall out. The clearances must still be larger to reach a targeted Z-length reduction of 50%.

Iteration Five. The last problems to be solved were increasing the Z-length reduction to 50% and preventing loose oak veneer tiles. ***Design process:*** The rim needed to be thicker, to create more friction for the oak veneer tiles. Therefore, the base was printed thinner, so that the number of layers remained the same. The clearances were 2 mm. ***Prototype:*** As with iteration five, magnets were used to hold the nylon tulle in place. The printing time was again 89 min. The oak veneer tiles were laser cut and fitted in place with adhesive on the back. The assembly took twelve minutes. ***Experiment:*** The targeted Z-length reduction was 0.58 equal to 58%. ***Analysis*****:** The clearances were large enough to achieve the 50% Z-length reduction and the oak veneer tiles did not fall off because of the friction and adhesive (Fig. 3).

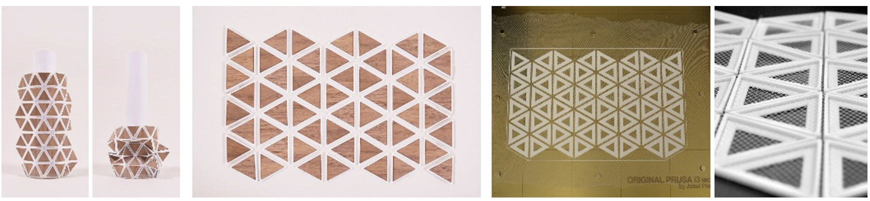

Fig. 3. Iteration Five: Experiment - top view hybrid material - fabrication

2.3 Results

An overview of the parameters of each iteration can be found below. Afterwards the fabrication process of the hybrid material is explained in detail as a guide for the intended end-users (Table 1).

Table 1. Iteration overview

Iteration	Materials	Shape	3D Print time (minutes)	Assembly time (minutes)
1	Cotton; oak, bamboo and meranti veneer; adhesive		/	60
2	Cotton; oak veneer; adhesive		/	15
3	PLA; nylon tulle; oak veneer		124	6
4	PLA; nylon tulle; oak veneer		89	6
5	PLA; nylon tulle, oak veneer; adhesive		89	12

Fixed Dimensions of Materials. To ensure a repeatable experiment with the hybrid material, following dimensions must be maintained. Nylon tulle: 122 mm to 123 mm. 56 triangular tiles in PLA: 20 mm to 17 mm to 1.1 mm. The diameter of the PLA is 1.75 mm. 56 wooden veneer tiles: 19 mm to 16 mm to 1 mm.

Hybrid Material Fabrication. The fabrication is done in four steps with a combination of PLA and nylon tulle. The 3D printer used here is the Prusa MK3s.

1. Generate the CAD model consisting of 56 triangular tiles spaced in seven rows and four columns, like the design in iteration five. Each tile consists of a base, 0.3 mm high, and a rim, 0.8 mm high. The clearances between the tiles are 2 mm.
2. Use PrusaSlicer to convert the model to Gcode and select PLA as material. ¨Print three layers at 0.1 mm layer height. Then, pause the print.
3. Place the nylon tulle on top and secure it with eight magnets (four magnets on the corners and four magnets at the centre of each side).
4. Print the remaining eight layers at 0.1 mm layer height on top of the nylon tulle and so encasing it between the prints.

Hybrid Material Customization. This process is optional. Multiple wooden veneer types can be used to customize the hybrid material to the users taste. The customization is done in three steps. The machinery used, is a laser cutter BRM 6090 (BRM Lasers, Netherlands), but can be done by hand.

5. Convert only the inner edges of the rim of the CAD model to a DXF-file. The BRM 6090 software sends the DXF-file to the laser cutter. Set the speed to 100 mm/s and the power to 60%. It takes one minute to laser cut 56 wooden veneer tiles or 30 min to cut them by hand.
6. Once done, snap fit the wooden veneer tiles in the triangular tiles. The rim creates enough resistance to hold the wooden veneer tiles in place.
7. Flip the hybrid materials and use transparent cellulose nitrate adhesive to glue the wooden veneer pieces to the nylon tulle. The gap in the base of the triangular tiles allows for an area large enough for the adhesive to be applied.

In total, the fabrication time is 102 min; 89 min to 3D print, one minute to laser cut and 12 min to assemble. The handwork, however, only takes 12 min.

3 Design Exploration

3.1 Case Study

In the second phase, we conducted an explorative design-case study with the objective to test the material's flexibility and the fabrication approach. Here, the hypothesis was to test the aesthetics of the hybrid material as a shape-changing interface, implemented in an intuitive flowerpot design. When water evaporates and nutrients are cut short, the plant starts to shrink, corrugate and eventually collapse. The experiment was conducted with six participants, all schooled in Interaction Design. They were asked to evaluate three interactive motions and if the hybrid material was suitable here for.

The hybrid material for this experiment had a size of 133 mm to 268, with seven rows of 20 triangular tiles on it. With this length, a full cylindrical shape could be made with a diameter of 150 mm. Inside the flowerpot, a linear mechanism moved the hybrid material vertically between its stretched and the corrugated position. A servo motor, controlled by an Arduino, powered the actuated motion in a Wizard of Oz test-up. In real-life, the actuated motion would be controlled by environmental sensors. LED's inside the flowerpot aided the interactive motions through colour changes. Using a variable resistor, operated by the observer, the servo could be controlled (Fig. 4).

Fig. 4. Test set up (left: stretched position - right: slightly corrugated position)

3.2 Experiment and Verification

The three interactive motions are a stretched position, a corrugated position and a pulsating motion. We try to anthropomorphise the flowerpot through these motions.

Stretched Position. The flowerpot finds itself in its normal state. A white LED-light implicates a natural feeling. The purpose of this interaction is to communicate that the plant is healthy; enough water, nutrients and sunlight.

Corrugated Position. The flowerpot finds itself in a corrugated position. It has shrunk, thereby creating a corrugated effect indicating that the plant has dried-out because one of nutrients is missing. The red LED-light implicates danger. The participant needs to replenish the growth factor.

Pulsating Motion. The flowerpot pulses between the stretched position and the corrugated position of 25% instead of 58%. This interactive motion simulates joy. It occurs when the plant wants attention or when one or multiple growth factors of the plant is replenished. This pulsating motion tested the hybrid material to its limits.

4 Conclusion and Future Work

The fabrication approach of this hybrid material can be used by creative intended user, but it is only applicable on small scale. With larger clearances, the Z-length reduction, can even be greater than 58%, but this results in the hybrid material being more see-through. Field of application are, for example, the fashion industry as proven by Iris van Herpen, engineering or advanced shape-changing interfaces [3]. Experiments on different specifications, increasing size, communicative properties etc. of this hybrid material does however need further research. Moreover, measurable specifications such as robustness, yield strength, e-modulus etc. also need to be determined.

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