WeaveMesh: A Low-Fidelity and Low-Cost Prototyping Approach for 3D Models Created by Flexible Assembly

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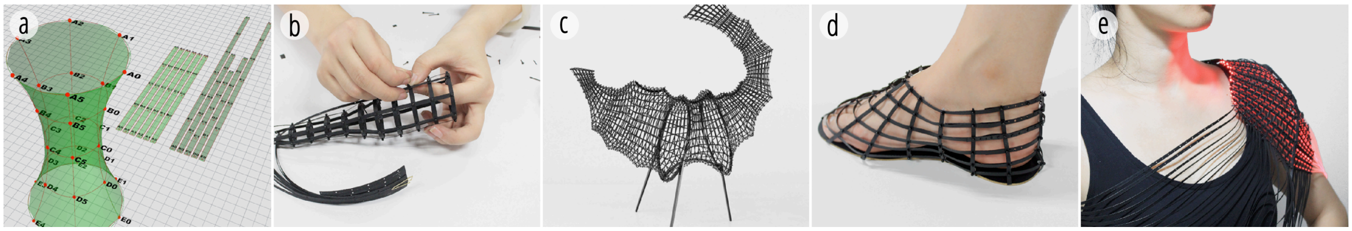

Figure 1. WeaveMesh system. (a) Software platform for customizable mesh; (b) Manual assembly with low-cost material and connectors; (c) Outcome of one test: an abstract sculpture with multiple surfaces; (d) Created a fitted shoe by flexible assembly; (e) Outcome of one test: an interactive cape attached with optical fiber.

ABSTRACT
To meet the increasing requirements of HCI researchers who are prototyping a variety of forms to create novel interfaces under a ubiquitous situation, we present WeaveMesh, a low-fidelity and low-cost rapid prototyping system that produces 3D objects in a mesh structure. Inspired by hand-weaving craft, WeaveMesh supports a highly customizable software platform, which is applicable for simulating and facilitating freeform surface constructions composed of woven lines arranged in a regular grid, which can serve as a guide for easy assembly. In addition, mobilizable connectors are suggested to support flexible assembly, which can be revised, recycled, and reused to facilitate short iterations. Furthermore, compared to common additive and subtractive techniques, WeaveMesh has a better balance between time and material saving. In this paper, we will introduce the system in detail and demonstrate the feasibility of the technique through various 3D models in the area of interactive media, products and architecture.

Author Keywords
Rapid prototyping; low-fidelity fabrication; UV mesh.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User interfaces.

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INTRODUCTION
Common rapid prototyping tools, such as 3D printers and laser cutters, as a way of data-driven production, impel HCI researchers to create digital fabrication methods that are not dependent on machines. A low-fidelity fabrication approach was achieved to speed up all intermediate versions. Unfortunately, the one-off objects fabricated in each version cost actual material waste, and the irreversible process inevitably slowed down design iterations.

We therefore argue that the process of rapid fabrication for quick design iterations is not yet optimal. In other experiences, such as traditional craft, artisans have achieved an efficient method through constant modification during the process of production. In product design, low-fidelity techniques, such as sketching and draft prototyping give designers an easy trial-and-error procedure. This tradeoff is effective in the early design stages, because it encourages designers to try various versions before investing additional resources, thus resulting in superior designs [7]. A similar concept, flexible assembly technology, is applied in industrial production. The reconfigurable assembly method improves adaptability and reduces cost, especially for modern personalized demands [31].

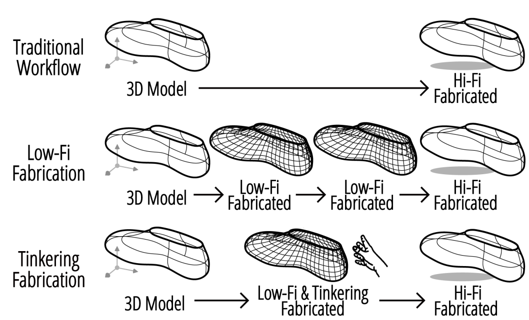


Figure 2. Tinkering fabrication: only one intermedia version is fabricated as fast assembly and manual adjustment.

We argue that the same principle should be applied to rapid prototyping, as concept tinkering can be viewed as a valid and valuable style of engaging with a project [29]. In contrast to the data-driven workflow, in which the 3D model is fabricated followed by data revision in each iteration, manual tinkering gives an intuitive impression to guide users constantly trying out ideas, making adjustments and refinements, and then experimenting with new possibilities until they are ready to fabricate the finished high-fidelity version (Figure 2).

In this paper, we present WeaveMesh (established on our preliminary works [32, 33]) as a novel low-fidelity and low-cost fabrication approach that is not only fast but also fully flexible in terms of assembly in the early stage of the design process. The key idea is to replace the 3D surfaces with a computational UV mesh. The software platform outputs assembly instructions that are marked on widely used materials (e.g., paperboard, pp films, bamboo pieces, etc.) using a cutter machine. Tinkering as a style of making requires manual involvement, such as assembling and modifying, to construct the final prototype. At the same time, mobilizable connectors are suggested to support flexible assembly, which can be revised, recycled, and reused to facilitate short iterations. In short, WeaveMesh system could push different stages of the iteration process:

1) For functional iteration: With low-cost materials, flexible shape attributes, and mesh characteristics, WeaveMesh can be a prototype carrier. For instance, in HCI research, it can be easily combined with other hardware (e.g., in the installation of sensors and actuators, or in combination with optical fiber), so feasibility tests can accelerate the functional iteration process.

2) For concept iteration: The manual assembly provides user behavior and action space, which also leads to the generation of new ideas. For example, users will get feedback from each step when building physical objects through hand working then make decisions, thus increasing their opportunity to propose better design solutions.

3) For digital/accurate iteration: it provides a series of widgets to support the loop from physical to digital for accurate iteration.

We will introduce the system in detail and validate the feasibility through various 3D models later in this paper.

RELATED WORK

The work presented in this paper builds on the notions of personal fabrication, interactive fabrication, rapid fabrication of 3D objects and making objects in meshes.

Personal Fabrication

Personal fabrication devices such as laser cutters and 3D printers allow users to create physical objects rapidly [16]. To lower the entry barrier for nonprofessional users to personal fabrication, a number of HCI researchers have developed new approaches that make the path to prototyping much smoother. For instance, *SketchChair* [30] and *Plushie* [21] allow novice users to customize objects with drawing; Lau et al. [19] presented a furniture-making approach with automatically generating fabricatable parts and connectors from a 3D virtual model. In the study of 3D printing, different approaches have been explored in terms of materials (*xPrint* [35, 36]), modeling methods (*MixFab* [37]), application fields (*ExoSkin* [14]), etc. Generally, researchers have emphasized that personal fabrication is increasingly ubiquitous through the development and availability of new user-friendly and low-cost technologies.

Interactive Fabrication with Craft

Inspired by traditional craft activities which provides real-time physical feedback, Willis et al. [38] proposed interactive fabrication. It is not surprising to see that more digital mediums have been reintroduced to craft and hybrid materials. Amit Zoran's group created a range of projects (*FreeD* [42], *Hybrid Basketry* [41], *The Hybrid Bricolage* [13], etc.) to discuss more about how the new digital techniques contribute to traditional craft during the process of hand-making. In addition, a number of projects demonstrated new ways of combining modern fabrication with material-based craft (e.g., clay [18], wax [26], fabric [11], everyday materials [12]). Like these systems, we draw inspiration from weaving craft to develop WeaveMesh, which allows users to engage in the process of fabrication.

Rapid Fabrication of 3D Objects

In the field of rapid fabrication, several new solutions have been proposed to speed up the process of prototyping based on laser cutters or 3D printers. *faBrickation* [24] uses Lego bricks to replace most of the model volume and only 3D-print regions where high resolution is required. *Platener* [6] follows the same idea by converting the bulk of the volume into laser-cuttable parts while using 3D-printed parts for complex shapes. *LaserOrigami* [23] shows a novel rapid prototyping system that produces 3D objects with a laser cutter by cutting and folding an acrylic sheet. Unlike *Autodesk 123D Make* [2], a rapid prototyping software program that involves simple converting a 3D model into planar slices, *CardBoardiZer* [40] allows users to build foldable and articulable objects using cardboard material in less time. To expand the existing approaches to rapid fabrication for 3D creations, we propose a new molding solution by converting a 3D model into a mesh structure on the surface and further into planar pieces for manual assembly.

Making Objects in Meshes

Previous research has led to a variety of mesh methods for 3D prototyping. *WirePrint* [22] and *On-The-Fly Print* [25] were proposed to print mesh edges directly, saving significant time to give designers a quick preview of 3D models. With the goal of printing 3D wireframes using arbitrary meshes, Wu et al. [39] proposed an algorithm to generate plans for 5DOF printers. For the non-printing fabrication system, Cignoni et al. [8] introduced an innovative method that allows users to produce complex fabricable structures. Instead of converting an existing 3D model to intersecting pieces, *FlatFitFab* [20] enables users to manipulate mesh designs directly from laser-cuttable parts. In addition, *Protopiper* [5] is a handheld fabrication device that allows users to prototype large-scale objects in wireframe mode with plastic tubes. On the commercial side, many design tools have been demonstrated to expand the space of mesh design, such as the handheld 3D printing pen *3Doodler* [1], comprehensive 3D editor *Autodesk 123D Make* [2], and building block toy *Zometool* [4].

On the other hand, objects made from meshes may provide a better aesthetic experience. Many artists, such as Cooper [10] and Taylor [34], consider wire meshes as a popular medium in abstract and figural sculptural art design. Garg et al. [15] developed a computational approach for designing similar wire mesh structures with temporary wooden grids. In our work, we seek a middle ground of making mesh objects efficiently while ensuring they are aesthetically pleasing.

WEAVEMESH SYSTEM

The system is inspired by the traditional hand-weaving molding technique, which is characterized by woven strips that cover the surface instead of filling the entity. Compared to common 3D printing, the method relies on the twisted structure of the mutual restraint force of the woven strips, not the adhesive properties of the material. This implementation is what ensures the structure's flexibility. The weaving characteristic and tinkering with indigenous materials also inspired us to expand the possibilities of weaving mesh structures in modern manufacturing technology.

WeaveMesh contains a software platform developed on top of Rhino and Grasshopper plugins [17] and manual-aided hardware connectors. WeaveMesh is designed with a few goals in mind:

1) The system needs to ensure an easy and accessible technique for non-experts according to the specification.

2) The software platform should provide highly customizable tools that can accommodate different shapes, such as shape segmentation and joints, resolution definitions, strip sizes and mesh assembly specification.

3) The technique should provide conditions for tinkering to take full advantage of the flexibility of mesh structures and to facilitate short iterations.

4) The physical prototype needs to be easily and rapidly made out of low-cost, accessible materials and tools, especially at the early conceptual design stages.

Workflow

In order to achieve the above mentioned design goals, WeaveMesh was created to produce customizable and low-fidelity mesh prototypes directly from digital 3D models. As shown in Figure 3, the workflow unfolds as follows: The user (1) inputs a desired 3D model in rhino software (Figure 3a), (2) customizes the mesh parameters with one surface once, such as quantity, direction, and width (Figure 3b), (3) develops the two-direction strip patterns with reference points ready to be cut (Figure 3c), and then (4) hand assembles (Figure 3d) and tangibly modifies (Figure 4) the prototype simultaneously to complete the iteration before finishing the high-fidelity version.

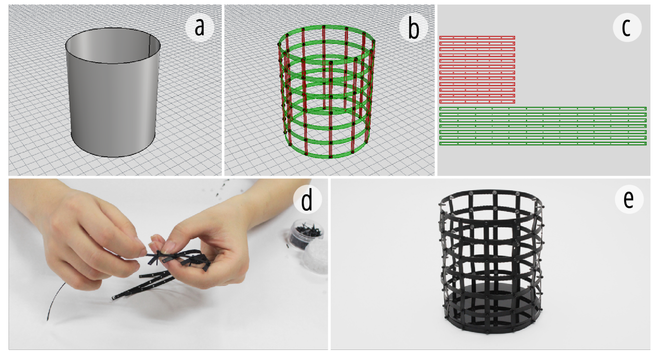


Figure 3. WeaveMesh workflow illustrated by a cup case: (a) creating a model in rhino software, (b) converting it into a mesh structure in Grasshopper, (c) simulating 2D pattern before cutting, (d) assembling, (d) obtaining first-version prototype.

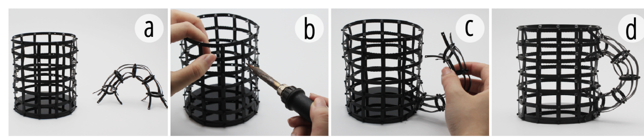


Figure 4. Tinker process: (a) adding one part. (b) making holes, (c) connecting two parts, (d) obtaining second-version prototype.

Customizable Mesh and Software

Here, the implementation of first-edition WeaveMesh software is performed to analyze the UV mesh mapping of a single surface of a 3D model separately.

UV mesh mapping

The UV mapping is operated on Grasshopper in Rhino software. It transfers the surface into two lists of curves, and the curves are the lists of the points. To avoid confusion, we name the two lists of curves M and N respectively. As shown in Figure 5, we do the UV mapping in the cup as an example. The parameters for M and N are 6 and 5. Therefore, we get two curve lists as follows:

M = {	N ={
(A0, B0, C0, D0, E0),	(A0, A1, A2, A3, A4, A0),
(A1, B1, C1, D1, E1),	(B0, B1, B2, B3, B4, B0),
(A2, B2, C2, D2, E2),	(C0, C1, C2, C3, C4, C0),
(A3, B3, C3, D3, E3),	(D0, D1, D2, D3, D4, D0),
(A4, B4, C4, D4, E4),	(E0, E1, E2, E3, E4, E0)}
(A0, B0, C0, D0, E0)}	

Point A0 can be initialized with any point on one of the edges in Figure 5b, and then the other points are initialized after A0.

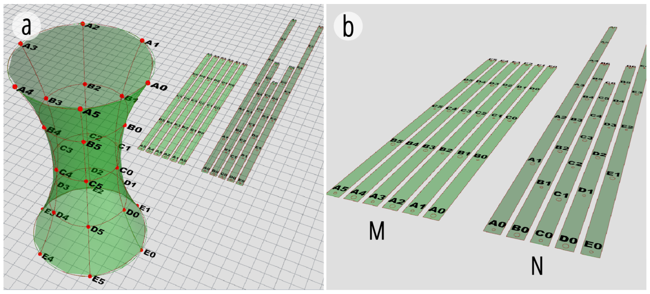


Figure 5. WeaveMesh interface: (a) UV mesh mapping, (b) 2D pattern and specification.

Vertices property

In the traditional weaving craft process, one of the biggest problems faced by non-experts is staggering up or down between two strips. Although there is no need to keep the weaving method in the actual assembly process benefit by connecting components, we retain and extend the "one warp, one weft" [9] characteristic in the software to make it applicable to hand-weaving methods, facilitate manual operation, and reduce the risk of errors in connecting a number of UV strips. Based on UV mapping, we assign each point an upper/lower property and set them opposite to each other. Here is a pseudocode of the varying diamond pattern:

```
Input: the 2-D arrays M and N
Mark the point A0 as UPPER point
Let p be the point A0
for each neighbor point np of p with no mark do
        mark np as the opposite to p
        let p be the point np
        mark the corresponding points in N as the opposite
```

2D pattern and specification

Since the UV strips are separate similar ones that are difficult to pick out in the manual process, we arranged for the order number in 2D pattern generation.

As the UV mesh map shows, the curves were automatically generated in two groups, M and N, and we straightened the curves without changing their lengths. As shown in Figure 5b, we put the lines on the coordinate plane in the order that they follow in M and N respectively. The alphabetical and numerical marks on the points of the curves map to the lines correspondingly. The points that share the same mark connect together, for example the B2 point of M and the B2 of N.

In manual work, users can fix group M first, rotate group N counterclockwise 90 degrees, overlap the M and N at right angles, and finally connect the corresponding vertices of the two groups together (Figure 5b).

Customizable tools

We offer tools to customize the parameters of the strips, such as the quantity and size of the UV strips and points (Figure 6).

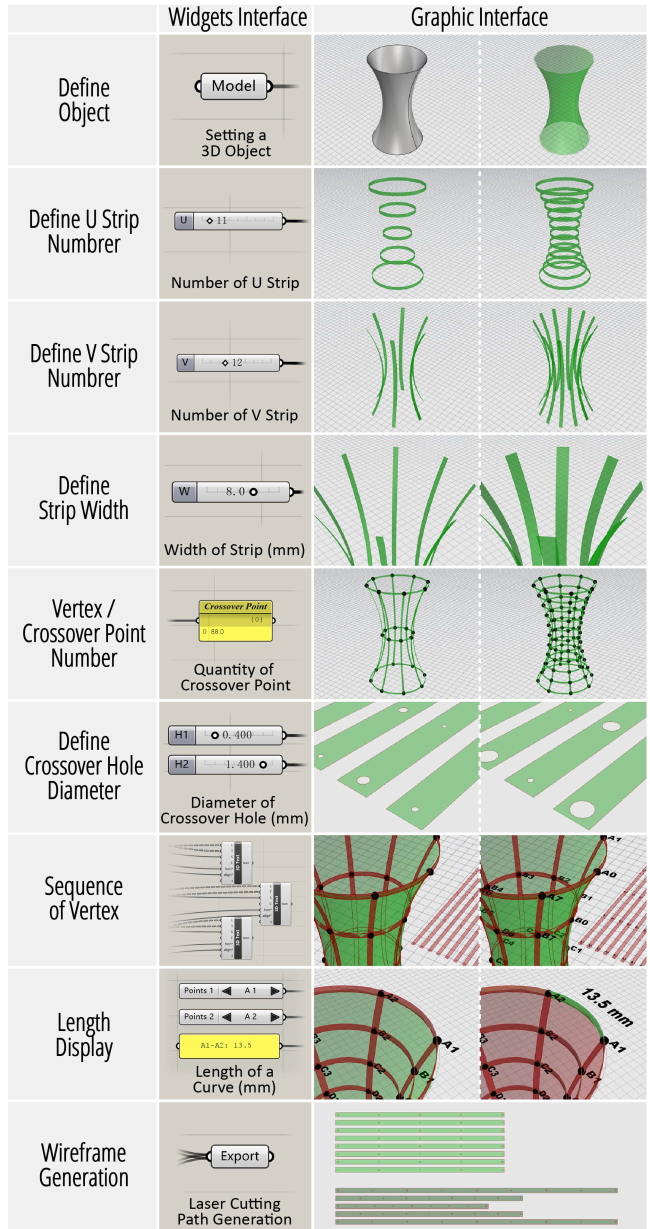


Figure 6. Customizable tools in WeaveMesh software.

Hardware

The hardware system includes a machine tool and connecting components. The machine tool is used to mark the reference points (i.e. apex crossed by UV strips) on the material. In our case, we use a laser cutter that help efficiently convert the digital patterns into flat prototypes. Otherwise, die-cutter, milling cutter, or hand cutter can be used.

Components are connected to fix UV strips at each apex position. As Figure 7a shows, it can across and stuck two strips together by the structure of thin middle and thick on both ends. In our case, we use low-cost earrings ($1 one hundred) or invisible fastenings ($6 one hundred) as the connecting components that can be used repeatedly and easily purchased.

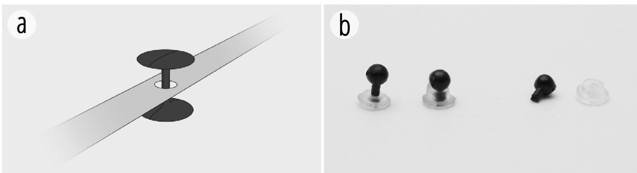


Figure 7. (a) The structure of connecting components; (b) The low-cost earring connectors used in this paper.

EXTENDING SYSTEM
In this section, we present extensions to our basic approach that allow us to handle additional scenarios.

Structure Library
A four-corner mesh structure is more flexible compared to a triangular mesh structure, especially when the vertices can be rotated. In tangible operating practice, we suggest that it can serve as a transformative and moveable model function. Here, we summarize two common structural examples of the activities for quick use.

Scalable structure: This can be applied for distance conversion. As Figure 8 shows, the mesh structure is built on a right circular cylinder composed of the weft rings and vertical warp strips. When the weft rings rotate, the warp strips tilt in the same direction; thus, the spaces between the wefts are reduced to achieve a shrink state. Reverse rotation, similarly, achieve a stretching state.

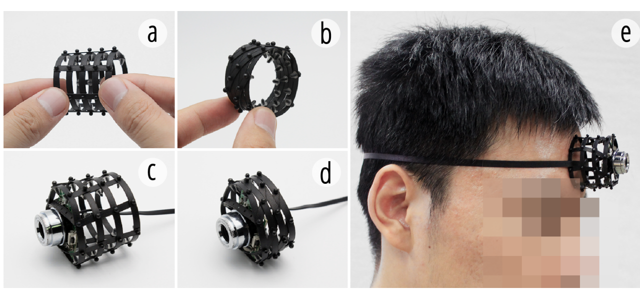


Figure 8. Scalable structure: (a) a stretching state, (b) a shrink state, (c, d and e) an application: a headset camera.

Belt clasp structure: This can be applied for dimensionality conversion, especially for wearable media areas. Like a belt, it is one strip with spaced distribution points, which can achieve one circular ring belts on different scales (Figure 9). Users can quickly choose the data file with the target size in the system.

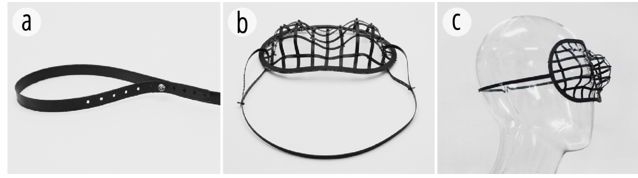


Figure 9. Belt clasp structure: (a) the belt, (b and c) an application: a blinder.

Material Options
This method is suitable for easy-to-cut material with elasticity and toughness properties. The elasticity guarantees curved surfaces in the actual model, because the mesh structure is built on the original model. It also requires a certain toughness that can support three-dimensional shapes. Due to immediate changes in the modeling process, the material should be easy to cut.

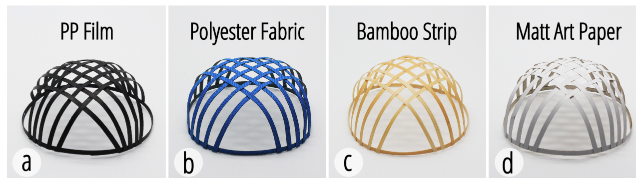


Figure 10. The candidate materials: (a) 0.3mm Thick Polypropylene (PP) Film; (b) 0.4mm Thick Polyester Fabric; (c) 0.25mm Thick Bamboo Strip; (d) 200g Matt Art Paper

The candidate materials include everything from natural materials to synthetic materials, but they should be inexpensive and as thin as paper. Figure 10 highlights the available materials that we have preliminary tested in UV mesh structures. As shown in Figure 10a, PP film, also known as polypropene, is used in a wide variety of applications including packaging and labeling, textiles, and reusable containers of various types. In the experiments, we selected it as the main material, because it has all the relevant properties of candidate materials with high strength, and can be easily and cheaply purchased (less than $3 one square meters).

EXPERIMENT AND RESULTS
The 0.45mm-thick PP film was used as the experimental material, and it is shown in Table 1 (on the next page) after the 2D pattern is generated and cut. For the overall cutting setup, we used a relatively higher speed (1000mm/s) and lower force (57 grams) laser cutter, and almost all the experimental items could be completed in less than 10 min of cutting. Our system requires manual user involvement, such as assembling and modifying to construct the final prototype.

Prototypical Results
Table 1 shows our prototypical results using 9 demonstrated examples. According to the WeaveMesh results on a number of 3D objects, our creative software platform allows more improvements for quick and easy assembly.

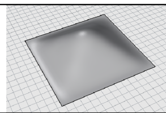
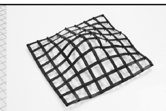
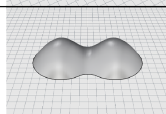
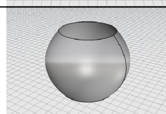
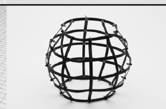
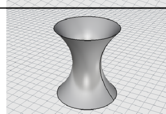
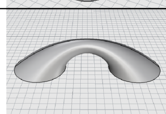
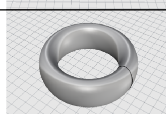
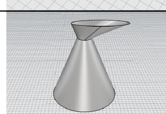
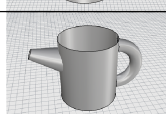
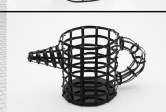
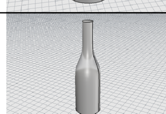
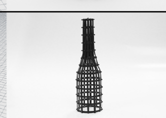
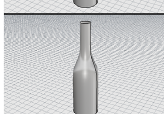
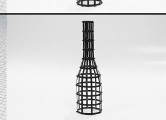
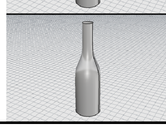
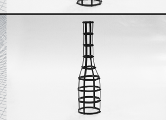
Name	Model	Prototype	Resolution (U × V Quantity)	Quantity of Vertex	Time Assembly (mm : ss)	Volume (L × W × H mm)	Pattern Area (L × W mm)	Material Utilization
(a) 2.5D Single Peak			9 × 9	81	15:56	140 × 140 × 38	171 × 90	92 %
(b) 2.5D Twin Peaks			5 × 9	45	10:06	154 × 94 × 28	209 × 56	63 %
(c) Fat Cylinder			5 × 10	50	12:08	108 × 108 × 80	341 × 60	89 %
(d) Thin Cylinder			5 × 10	50	12:38	70 × 70 × 80	224 × 60	86 %
(e) Arch Cylinder			9 × 8	72	15:24	216 × 76 × 46	282 × 72	67 %
(f) Circular Ring			8 × 8	64	20:16	106 × 106 × 36	382 × 60	88 %
(g) Two-Part Cap			Top: 7 × 14 Bottom: 15 × 14	308	78:58	215 × 190 × 230	643 × 116	64 %
(h) Three-Part Pot			Left: 6 × 5 Middle: 7 × 12 Right: 6 × 5	144	41:22	177 × 90 × 100	287 × 95	88 %
(i) Bottle Cylinder			12 × 13	156	35:02	50 × 50 × 180	192 × 96	83 %
			10 × 8	80	20:24	50 × 50 × 180	192 × 72	84 %
			8 × 4	32	08:29	50 × 50 × 180	192 × 48	96 %

Table 1. Experimental case collection.

Improved design

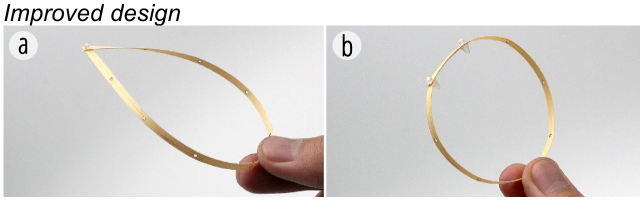


Figure 11. Circle structure: (a) corner problem, (b) improved design with two overlap points.

Circle structure: This is an essential part of the torus, which requires each strip to be connected end to end. In the actual connecting process, we found that corners often appeared when connecting the circle by one point of intersection, as shown in Figure 11. Therefore, we improved the generated 2D pattern by adding a point n+1 to each strip (n represents the last point of the original strip), making the circle structure fixed in a ring.

Figure 12. The improved 2D pattern was cut on the material.

2D pattern arrangement: This relates to the legibility of specification and the material utilization. We improved the arrangement so that the automatic generation pattern was divided into groups, and the groups of strips connected with each other without gaps (Figure 12). The related figure notation is also automatically generated.

Model resolution

In WeaveMesh, the user can intuitively set the resolution, because the software can simulate the UV mapping on the 3D model in real time while setting the quantity of UV strips. Meanwhile, the quantity of UV strips determines the quantity of vertices, the assembly time and material consumed correspondingly. In Table 1i, we tested the bottle model with three different resolution levels, R_l, R_m, and R_h, to provide a reference (R_l represents relatively low fidelity, R_m represents medium fidelity, and R_h represents relatively high fidelity).

Time Evaluation

In order to understand the construction efficiency using our system, we studied the relationship between the quantity of vertices and the speed of assembly of our 10 demonstrated prototypes (for more statistic see Table 1). Our experimental results showed that the assembly time is proportional to the quantity of vertices, which should be set at the optimal quantity of 50 to 360 for an item-sized model and take 12 to 90 minutes in manual assembly. The estimated time would be appeared in the software with the quantity of vertices calculate by 15 seconds for one vertex under comprehensive factors.

Material Evaluation

To speed up the transformation of the reference point from the vector data to the actual material, we selected planar material that can be cut by a laser cutter. All the target shapes were long strips that could be seamlessly arranged, thus significantly increasing material utilization compared to other irregular shapes. Table 1 shows the statistics on volume, material area, and utilization. Our experimental results showed that the material utilization appears in the range of 60% to 96%.

Usability Discussion and Comparison

Using WeaveMesh, the user is able to customize a 3D model through the choice of resolutions, quickly fabricate the pattern using cutters on demand, and complete the model through simple manual assembly and modification with connectors. It is fast and user friendly as users only need to load the digital 3D model and specify the parameters, and then the system generates the 2D patterns ready for cutting and assembly.

The selection of PP film as our building material offers accessibility to novice users. PP film and other similar sheet-like materials are low-cost everyday material that users are familiar with and can be easily accessed by novice users. Compared with other materials, such as acrylic, sheets can be cut by almost all cutting tools to support timely tinkering. The objects can be easily adjusted and enhanced by using scissors, soldering irons and components to cut, make holes and attach other objects or decorative materials (e.g., electronics, LEDs, and optical fibers). Tinkering with objects generated by WeaveMesh and other objects has multiple benefits for both learning and expression [27] as it invites broader participation and deepens the learning outcomes by allowing for a range of new solutions.

In order to better position the approach in practice, we further compared WeaveMesh with two common data-driven methods, additive and subtractive techniques, which have been widely used in the prototyping field of HCI research. We herein carefully compare the workflow, ease of interaction, fabrication statistics, and final prototypical results using the interlocked slices of Autodesk 123D Make (Table 2a) and 3D printer (Table 2b) and our WeaveMesh (Table 2c). The bracelet model was selected for all three methods with identical scales (10cm x 10cm x 4cm) and comparable resolution.

Approach	Prototype	Time of Preparation	Time of Assembly	Material Utilization
(a) Interlocked Slices		5min (Laser Cutting)	5min	18 %
(b) 3D Printing		14h 50min (or 1h 45min)	0min	100 %
(c) WeaveMesh		2min (Laser Cutting)	20min	88 %

Table 2. A bracelet case was fabricated respectively by (a) interlocked slices, (b) 3D printing, and (c) WeaveMesh.

In Autodesk 123D Make, the user is allowed to quickly manipulate the total number and orientation of planar sections with slots. We created the bracelet model with the same resolution as WeaveMesh in quantity of U and V, 4 and 8. In the 2D pattern, we found that the Autodesk 123D Make system generated regions with multiple shapes with large spare areas, which led to 82% wasted leftover material. In the 3D printing system, we used a general 3D printer with the Fused Deposition Modelling (FDM) [28] method by heating plastic material. It achieved almost 100% material utilization. However, it took in total 14 hours and 50 min to print the bracelet. As Mueller et al. presented a low-fi fabrication method can be 8.5 times faster [22], a 3D wireframe of the bracelet would take about 1 hour and 45 min. Our method, WeaveMesh required in total 22 min to fabricate with 88% material utilization. WeaveMesh was in the middle in terms of time and material consumption, provided a surface composition without occupied thickness, and exerted a more flexible space in manual modeling. In addition, the users needed dexterity and patience to keep track of the large number of individual parts, their locations and sequence for assembly.

APPLICATION

To demonstrate WeaveMesh, we now present three application examples of custom-fabricated objects. They instantiate diverse dimensions of the design space and demonstrate the potential for applications in interaction design, architectural design, and ergonomics.

Interactive Fashion Design

Technology of interaction has been increasingly integrated into fashion design. For instance, *Caress of the Gaze* [3] was created as a 3D printed garment that detects and responds to the gaze of others. To show how WeaveMesh will contribute to fashion design with interactive technology, we assembled a cape in 1.5 hours (Figure 13a). Furthermore, we weaved optical fibers within holes from the mesh and set up a sensing system with an optic PPG sensor. The pulse data was converted to the LED's color signal shown with optical fibers. Figure 13d and Figure 13e depict the color expression with heartbeat data during relaxation and a deep-breathing exercise.

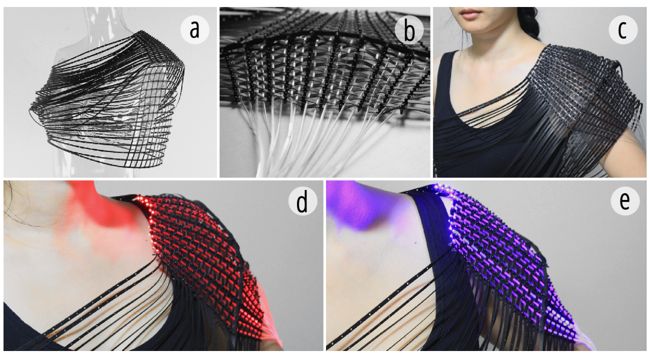


Figure 13. An interactive cape was created using WeaveMesh as a support texture for optical fiber.

Building Models and Art Works

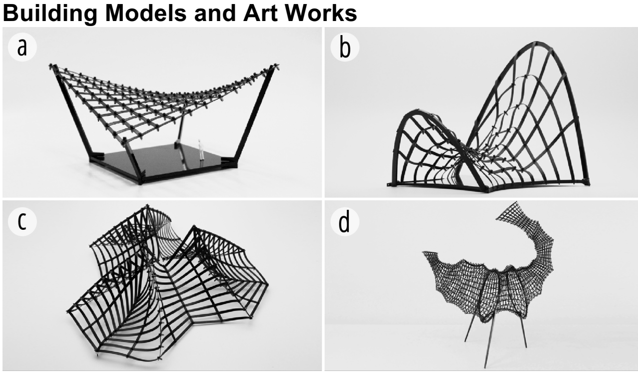


Figure 14. Surface composition in four cases was illustrated in different ways using WeaveMesh: (a, b) single-surface supported by stiff acrylic; (c, d) multiple surfaces connected with each other.

With the property of mesh, WeaveMesh can be used as a new approach with unique aesthetic characteristics to make models for architecture and art. We have prototyped three buildings and one art work with different surface designs. An independent surface was fabricated as the roof, which provided with adaptability and flexibility (Figure 14a, b), while a tent model was composed of multiple surfaces (Figure 14c). A large-scale sculpture was assembled with multiple surfaces (Figure 14d).

Industrial Design

Through this application, we intend to demonstrate that WeaveMesh is a quick method of enabling users to sense the physical size of virtual models during the design process. In addition, it speeds up the iteration process with a fast trial-and-error procedure. We designed a 3D shoe model as shown in Figure 15a and then made the physical object with a mesh upper and cardboard sole in equal proportion (we assembled the shoe's upper in around 17 minutes and the joint upper with sole in 8 minutes) (Figure 15b). It was found that the heel part of this shoe was a little small when a girl tried it on. We disassembled and expanded the strips of the heel part until it fitted well, which took 5 minutes (Figure 15c,d). In the following steps, we measured the length of the expanded stripes between two identified points (Figure 15g), while the 3D model curves were modified to correspond to the physical lengths with length display widget (Figure 6), then generated the final model (Figure 15h).

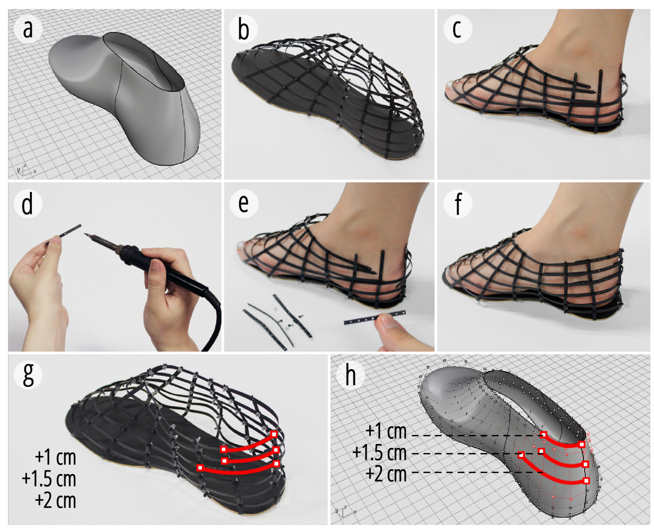


Figure 15. A fitted shoe was created by flexible assembly.

DISCUSSION, BENEFITS, AND LIMITATIONS

In WeaveMesh, the workflow can be operated as 3D-2D-3D (3D modeling in digital software, convert the model to 2D meshes' strips, and assemble the 2D strips to 3D physical model). The goal of WeaveMesh is supportive for early prototyping and iterative design.

To make our approach applicable to a wide range of users, we demonstrated how to create the specifications and shown that users can easily learn how to assemble and tinker with both dynamic and static models. For example, when a HCI researcher is willing to make an interactive cape (Figure 13) to inquire into the deep relationship between light and emotion, WeaveMesh provides a familiar workflow: 3D-2D-3D; if an artist has a higher aesthetic requirement, WeaveMesh achieves a desirable artistic effect with smooth curves or mesh patterns (Figure 14); when an industrial designer intends to design a pair of shoes with suitable size, WeaveMesh speeds up the iteration process with a fast trial-and-error procedure (Figure 15).

Conversely, our approach is not suitable for advanced design stages. For instance, when users need to test their design's physical strength, or objects are required to perform mechanical functions. In addition, WeaveMesh is limited in its ability to recognize the surface normal, that is, some double-sided surfaces rely on manual operation to determine the direction (Figure 16).

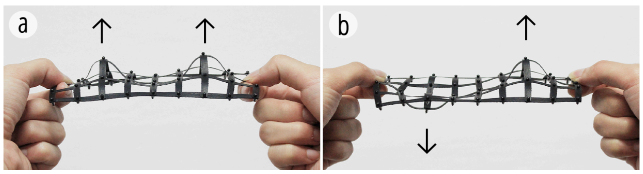


Figure 16. Limitation in recognizing double-sided surfaces.

For the formation of the shape, WeaveMesh can achieve 2.5D surface, cylinder, ring body and their variants. It is limited in large curvature of surface, such as the ring body (Figure 17), the top U strip of the ring cannot stick on the V strips because it will bend V strips at right angles to perpendicular direction. In such cases, it can be formed at the less than 45 degrees angle benefiting from the elasticity of material. However, a bigger angle would cause a bigger error on surface.

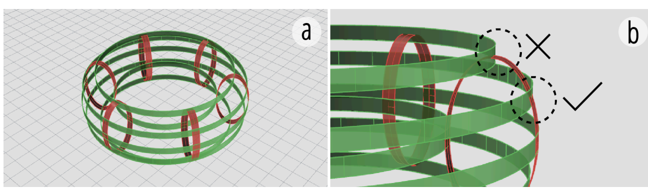


Figure 17. Limitation in prototyping a large curvature of a surface.

CONCLUSION AND FUTURE WORK

In this paper, we proposed a novel approach to low-fidelity 3D prototyping, i.e., covering a filled model and guided with a UV mesh map to enable easy manual assembly. Our experiment and evaluation showed that this approach could be easily operated and has a better balance between time and material saving, which makes it even more affordable for users to tinker and iterate.

Currently, we use a general UV mapping algorithm in which UV mapping is arranged homogeneously, thus limiting the restoration of big complex differences in a surface. For future work, a more advanced algorithm could separate a complex surface into different pieces to generate varied accuracy meshes that will better match the shape of 3D model. In addition, we will discuss more about room-size models and the material requirements for scaling up, such as thick and relatively flexible materials (e.g. bamboo strips in Fig.10) with more width sizes and bamboo weaving architecture as a reference. Certainly, more experiments on material selection, mesh location, connection, etc. are required.

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REFERENCES

1. *3Doodler*. Available from: http://the3doodler.com/.
2. *Autodesk 123D Make*. Available from: http://www.123dapp.com/make.
3. *Caress of the gaze*. Available from: http://behnazfarahi.com/caress-of-the-gaze/.
4. *Zometool*. Available from: http://www.zometool.com/.
5. Agrawal, H., Umapathi, U., Kovacs, R., Frohnhofen, J., Chen, H.-T., Mueller, S., Baudisch, P. 2015. Protopiper: Physically Sketching Room-Sized Objects at Actual Scale. *Proc. of UIST 2015*, 427-436.
6. Beyer, D., Gurevich, S., Mueller, S., Chen, H.-T., Baudisch, P. 2015. Platener: Low-fidelity fabrication of 3D Objects by substituting 3D print with laser-cut plates. *Proc. of CHI 2015*, 1799-1806.
7. Buxton, B. 2010. *Sketching user experiences: getting the design right and the right design*. Morgan Kaufmann.
8. Cignoni, P., Pietroni, N., Malomo, L., Scopigno, R. 2014. Field-aligned mesh joinery. *ACM Transactions on Graphics (TOG) 33*, 11.
9. Collier, A.M. 1970. *A handbook of textiles*. Pergamon Press.
10. Cooper, R. *Shadow sculpture*. Available from: http://www.randycooperart.com.
11. Devendorf, L., Lo, J., Howell, N., Lee, J.L., Gong, N.-W., Karagozler, M.E., Fukuhara, S., Poupyrev, I., Paulos, E., Ryokai, K. 2016. I don't Want to Wear a Screen: Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. *Proc. of CHI 2016*, 6028-6039.
12. Devendorf, L., Ryokai, K. 2015. Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication. *Proc. of CHI 2015*, 2477-2486.
13. Efrat, T.A., Mizrahi, M., Zoran, A. 2016. The Hybrid Bricolage-Bridging Parametric Design with Craft through Algorithmic Modularity. *Proc. of CHI 2016*, 5984-5995.
14. Gannon, M., Grossman, T., Fitzmaurice, G. 2016. ExoSkin: On-Body Fabrication. *Proc. of CHI 2016*, 5996-6007.

15. Garg, A., Sageman-Furnas, A.O., Deng, B., Yue, Y., Grinspun, E., Pauly, M., Wardetzky, M. 2014. Wire Mesh Design. *ACM Transactions on Graphics (TOG) 33*, 66.
16. Gershenfeld, N. 2008. *Fab: the coming revolution on your desktop--from personal computers to personal fabrication*. Basic Books.
17. Grasshopper. Available from: http://www.grasshopper3d.com/.
18. Jones, M.D., Seppi, K., Olsen, D.R. 2016. What you Sculpt is What you Get: Modeling Physical Interactive Devices with Clay and 3D Printed Widgets. *Proc. of CHI 2016*, 876-886.
19. Lau, M., Ohgawara, A., Mitani, J., Igarashi, T. 2011. Converting 3D furniture models to fabricatable parts and connectors. *ACM Transactions on Graphics (TOG) 30*, 85.
20. McCrae, J., Umetani, N., Singh, K. 2014. FlatFitFab: interactive modeling with planar sections. *Proc. of UIST 2014*, 13-22.
21. Mori, Y., Igarashi, T. 2007. Plushie: an interactive design system for plush toys. *Proc. of ACM Transactions on Graphics (TOG)*, 45.
22. Mueller, S., Im, S., Gurevich, S., Teibrich, A., Pfisterer, L., Guimbretière, F., Baudisch, P. 2014. WirePrint: 3D printed previews for fast prototyping. *Proc. of UIST 2014*, 273-280.
23. Mueller, S., Kruck, B., Baudisch, P. 2013. LaserOrigami: laser-cutting 3D objects. *Proc. of CHI 2013*, 2585-2592.
24. Mueller, S., Mohr, T., Guenther, K., Frohnhofen, J., Baudisch, P. 2014. faBrickation: fast 3D printing of functional objects by integrating construction kit building blocks. *Proc. of CHI 2014*, 3827-3834.
25. Peng, H., Wu, R., Marschner, S., Guimbretière, F. 2016. On-The-Fly Print: Incremental Printing While Modelling. *Proc. of CHI 2016*, 887-896.
26. Peng, H., Zoran, A., Guimbretière, F.V. 2015. D-Coil: A Hands-on Approach to Digital 3D Models Design. *Proc. of CHI 2015*, 1807-1815.
27. Peppler, K. 2013. STEAM-Powered Computing Education: Using E-Textiles to Integrate the Arts and STEM. *Computer 46*, 38-43.
28. Prajapati, D., Nandwana, S., Aggarwal, V. Fused Deposition Modelling.
29. Resnick, M., Rosenbaum, E. 2013. Designing for tinkerability. *Design, make, play: Growing the next generation of STEM innovators*, 163-181.
30. Saul, G., Lau, M., Mitani, J., Igarashi, T. 2011. SketchChair: an all-in-one chair design system for end users. *Proc. of TEI 2011*, 73-80.
31. Spinadel, P., Fugger, E. 1989. The technology approach to flexible assembly. *Assembly Automation 9*, 195-199.
32. Tao, Y., Lu, N., Zhang, C., Wang, G., Yao, C., Ying, F. 2016. CompuWoven: A Computer-Aided Fabrication Approach to Hand-Woven Craft. *Proc. of CHI 2016 Extended Abstracts*, 2328-2333.
33. Tao, Y., Wang, G., Zhang, X., Yao, C., Ying, F. 2015. A weaving creation system for bamboo craft-design collaborations. *Proc. of SIGGRAPH Asia 2015 Posters*, 3.
34. Taylor, N. *Wire mesh sculpture*. Available from: http://www.nikkitaylorsculpture.co.uk.
35. Wang, G., Yao, L., Wang, W., Ou, J., Cheng, C.-Y., Ishii, H. 2016. xPrint: A Modularized Liquid Printer for Smart Materials Deposition. *Proc. of CHI 2016*, 5743-5752.
36. Wang, G., Yao, L., Wang, W., Ou, J., Cheng, C.-Y., Ishii, H. 2015. xPrint: from design to fabrication for shape changing interfaces by printing solution materials. *Proc. of SIGGRAPH Asia 2015 Posters*, 7.
37. Weichel, C., Lau, M., Kim, D., Villar, N., Gellersen, H.W. 2014. MixFab: a mixed-reality environment for personal fabrication. *Proc. of CHI 2014*, 3855-3864.
38. Willis, K.D., Xu, C., Wu, K.-J., Levin, G., Gross, M.D. 2011. Interactive fabrication: new interfaces for digital fabrication. *Proc. of TEI 2011*, 69-72.
39. Wu, R., Peng, H., Guimbretière, F., Marschner, S. 2016. Printing arbitrary meshes with a 5DOF wireframe printer. *ACM Transactions on Graphics (TOG) 35*, 101.
40. Zhang, Y., Gao, W., Paredes, L., Ramani, K. 2016. CardBoardiZer: Creatively Customize, Articulate and Fold 3D Mesh Models. *Proc. of CHI 2016*, 897-907.
41. Zoran, A. 2013. Hybrid Basketry: Interweaving Digital Practice within Contemporary Craft. *Leonardo 46*, 324-331.
42. Zoran, A., Paradiso, J.A. 2013. FreeD: a freehand digital sculpting tool. *Proc. of CHI 2013*, 2613-2616.