FusePrint: A DIY 2.5D Printing Technique Embracing Everyday Artifacts

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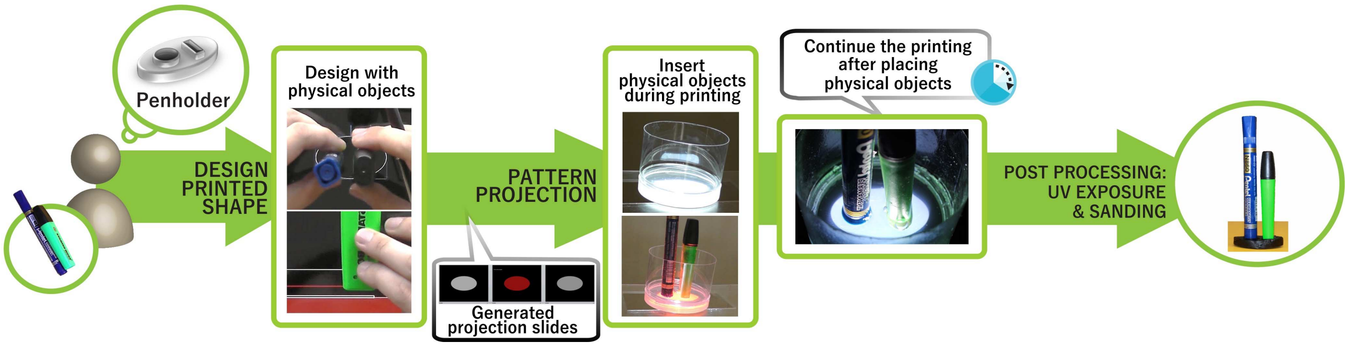

Figure 1: FusePrint fabrication process. User wants to create a penholder; its shape is designed with the reference of physical objects, and projected through the bottom of the container holding the resin and physical objects (pens). The projected shape solidifies, resulting in being perfectly matched to the objects.

ABSTRACT
FusePrint is a Stereolithography-based 2.5D rapid prototyping technique that allows high-precision fabrication without high-end modeling tools, enabling the mixing of everyday physical artifacts and liquid conductive gels with photo-reactive resin during the printing process, facilitating the creation of 2.5D objects that perfectly fit the existing objects. Based on our polynomial model on 2.5D resin printing, we developed the design interface of FusePrint, which allows users to design the printed shapes using physical objects as references, generates projection patterns, and notifies users when to place the objects in the resin during the printing process. Our workshops suggested that FusePrint is easy to learn and use, provides a greater level of interactivity, and could be useful for a wide range of applications domains including: mechanical fabrication, wearable accessory, toys, interactive systems, etc.

Author Keywords
FusePrint; Fabrication; DIY; 3D Printing; 2.5D Printing; Stereolithography; Everyday Artifacts.

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INTRODUCTION
The popularity of 3D printing technology has significantly boosted personal fabrication in the past decade. Although 3D printing has become increasingly precise, using it to create objects that can tightly fit with real-world artifacts can still be challenging [8] despite the availability of tools to create 3D models from existing objects, such as CADScan's Cubik® 3D scanner [6] and MakerBot's Digitizer [21]. This is because physical objects can have complex geometric structures (e.g., an internal screw thread). While fitting objects within a simpler structure, such as a cube, is theoretically easy, in practice, daily wear and tear may transform parts or the whole of that simple object into a more complex shape/texture, increasing the difficulty of modeling. High-end 3D scanning devices [1] can achieve greater precision, but they are usually costly and less accessible for hobbyists.

Even if a perfect 3D model can be created, much of the printing process in current low-cost 3D printers may introduce additional errors due to the difficulty in calibration(e.g., it can be difficult to 3D-print the details of an internal screw thread in an object to tightly fit the existing screws). These factors could result in a long chain of trial-and-error attempts with current 3D printers to produce objects that fit existing artifacts well.

One way to print objects (e.g., an internal thread) that can tightly fit existing artifacts (e.g., an external screw thread) is to leverage existing artifacts as a mold so that the printing material in contact with the artifact can naturally fit to its shape and texture. This implies that the printer needs to be able to tolerate the insertion of arbitrary objects during the printing process (before the printing material is solidified) without causing too much interference to the construction of the intended 3D model. Shape Deposition Manufacturing (SDM) [24] provides the possibility of embedding actuators, sensors and other pre-fabricated functional components inside the product. However, SDM still requires the fabrication of molds that precisely fit the embedded parts, which leads to ad-hoc tolerance optimization by novice users [15]. To fabricate parts for well-fitting assembly, current SDM processes often requires users to amend the original models in an ad-hoc manner for optimal tolerance, making the entire process time-and-cost consuming for novice users [29].

The current 3D-printing process (i.e., Fused Deposition Modeling – FDM [9], Stereolithography – SLA [14], and Selective Laser Sintering – SLS [10]) do not support the insertion of physical objects in the printing process. While inserting physical objects may obstruct the printing head for FDM or the laser beam for SLS, SLA leverages the usage of the liquid resin that can be cured gradually using light sources, thus it becomes theoretically possible to mix it with existing objects to produce the desirable molding effect. However, "*introducing objects into the resin while the printer is running can damage the resin tank,"* and *"may also interrupt the printing process";* therefore, existing SLA 3D printer manufacturers (e.g., Formlabs [11]) clearly declare that *"mixing anything into the resin*" is neither supported nor recommended [12]. In addition, testing with commercial SLA/DLP printers, although possible, requires modifying its setup to clear the space above the resin occupied by the building plate, thus it is non-trivial without any technical detail from the companies.

To support such capability, the printing process adopted by existing SLA printers needs to be carefully modified and tested. In this paper, we present our first effort to enable the capability of inserting existing artifacts with FusePrint, a DIY SLA-based 2.5D printing technique that allows for the mixture of everyday physical artifacts as well as liquid conductive gel with the photo-reactive resin during the printing process, making it much easier to create 2.5D objects that tightly fit with the existing objects and thereby offering interactivity. Using FusePrint, one can simply place an external screw thread or a cup, for example, into the photo-reactive resin during the printing process to print an internal thread or a cup holder that perfectly matches the shape of the inserted objects. In addition, by mixing liquid conductive gel with the resin, one can print customized touch-sensitive interactive objects that can detect multi-touch points as well as gestures.

As a first attempt, our DIY FusePrint technique still has a few limitations: it only permits the printing of 2.5D objects instead of true 3D objects, and the printing quality of the 2.5D object has a less polished finishing as compared with higher-end commercial products. However, with the new capability to include existing objects in the printing process without the requirement of prior modeling, FusePrint opens up new possibilities for personal fabrication and is already useful as a rapid prototyping tool for a wide range of applications domains.

The contribution of this work is threefold:

- A new SLA-based fabrication technique that can integrate everyday artifacts into the printing process to produce 2.5D models that easily fit various shapes and sizes without high-end modelling tools.
- Experimental investigation to find the parameters for controlling the resin curing process using a Digital Light Processing (DLP) projector.
- A workshop study showing FusePrint's effectiveness and the various application scenarios that leverage the unique capabilities of our technique.

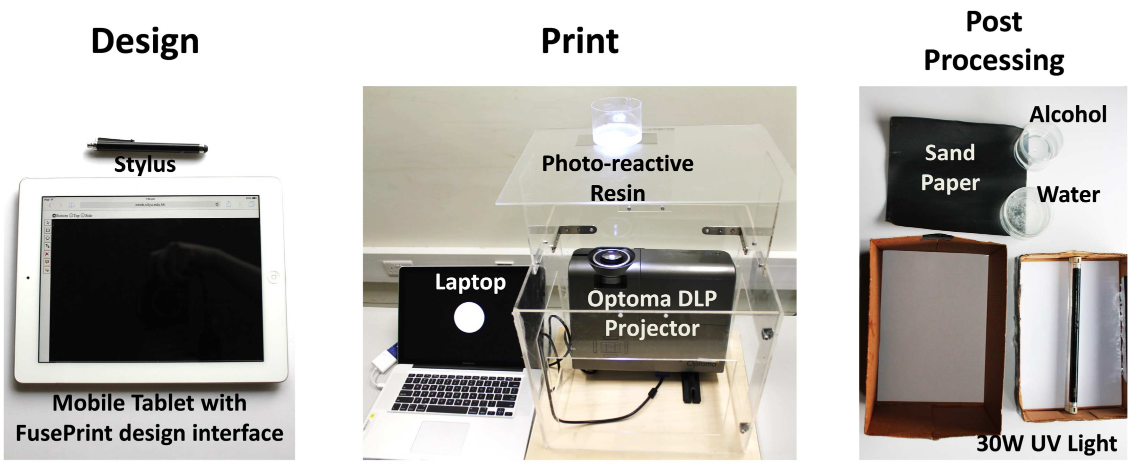
BACKGROUND AND RELATED WORK

Our design of FusePrint was inspired by the working principles of SLA 3D printers, the existing research in Human-Computer Interaction on integrating physical objects with 3D printing, and 3D printed interactive objects. We summarize key related work in these areas below.

Personal Fabrication with Existing Object

Researchers have long discovered the advantages of mixing existing artifacts with 3D created objects and have developed various tools to facilitate this process. For example, MixFab is a mixed-reality environment for personal fabrication, which allows users to create models by placing physical objects in the workspace [8]. KidCAD allows children to combine the 2.5D shape of their toys to create new 3D models for printing [27]. In CopyCAD, users can reuse 2D shapes in a CNC milling setting [28]. Constructable extends the 2D contour reuse by copying textures to workpieces [30]: a camera takes a photo of the texture and transfers it on the part using a laser-cutter. Enclosed [7] uses electronic components as handles and size references during enclosure design. It automatically adds cutouts to the enclosure patterns so that the components can be mounted. Printed Optics [16] adopted the shape-deposition-based process that still requires the detailed 3D models of embedded components. Similarly, the FDM-based Voxel8 [31] enables the fabrication of conductive circuit, but it still needs ad-hoc tolerance adjustment to integrate electronics.

More recently, Gannon et al. developed Tactum [20], which enables the design of 3D models for wearable accessories based on body shape. A review on rapid prototyping using laser-based, nozzle-based, and printer-based systems in the field of bioengineering shows how to combine 3D printed



(a) (b) (c)

Figure 2: FusePrint setup

structures with the human body [3]. Chen et al. [32] proposed Encore, an FDM-based 3D printing technique to augment everyday objects in three ways: printed-over, affixed, and interlocked. ReForm [35] leveraged the usage of malleable clay to allow users to create physical 3D models in a bi-directional way, and the physical clay models can be scanned and exported for 3D printing fabrication. It supported the usage of markers and physical objects as the annotation of modeling. In SPATA [36], Weichel et al. developed two technology-enhanced measuring tools, allowing users to transfer the geometric information of physical objects into 3D models. Teibrich et al. [37] presented a 3D-printing technique that supports direct modifications (i.e. addition and subtraction) on the already-printed objects using 3D scanning, to reduce the waste of the material because of the failures in fabrication.

In all mentioned work above, researchers have mainly focused on using physical objects in the modeling process. As previously mentioned, the modeling process itself can be tedious by requiring extra measuring tools, and errors could still occur during the scanning and the manufacturing process due to the non-perfect hardware implementation of FDM 3D printers. While Encore is the most relevant and competitive related work, FusePrint distinguishes itself as the fitting process of Encore assumes that "models of the existing and the new objects have been acquired using 3D scanning, or created from scratch". The Print-to-affix technique of Encore requires expert users to model a connector "that matches the surface geometry of the existing object", while in FusePrint, the real world object serve as a mold, which eliminates 3D scanning, and solves the problem of matching the surface geometry and modeling the connector.

3D Printed Interactive Object

Different approaches have been explored in printing functional actuators and sensors with FDM 3D printers. Ishiguro et al. [34] proposed the technology for designing and manufacturing interactive 3D printed speakers, where sound reproduction can be integrated into various objects at the design stage and little assembly is required. The same group further developed Printed Optics [16], a new type of 3D printed object that enables sensing, display, and illumination elements to be directly embedded in the casing or mechanical structure of an interactive device. Recently, Laput et al. [13] developed Accoustruments, a type of low-cost, passive, and powerless mechanisms for creating interactive mobile accessories, based on the principle of wind instruments.

FusePrint shares the vision of 3D printed interactive objects. Compared to these existing efforts with FDM 3D printing, FusePrint has adopted the process of SLA 3D printing, and we leveraged the usage of liquid resin and also explored the design option of mixing conductive gel to create 2.5D interactive objects that can support multi-touch interaction.

FUSEPRINT

FusePrint Setup

With FusePrint, we aimed to create a DIY process that could create objects to fit existing objects. As a DIY technique developed for hobbyists, we had the following design requirements for FusePrint:

1) The system is simple to setup and easy to maintain.
2) The cost is minimized by using existing tools.
3) The printing process is easy to learn and perform.

With these requirements, we developed a DIY setup (Figure 2) with four main components: a mobile tablet for shape designing, a light source using an existing Optoma DLP projector (model = EH1060; brightness value = 0; contrast value = 0), a resin container, and a computer. The DLP projector is mounted in the acrylic case, projecting upward to the container filled with photo-reactive resin. The resin container is placed on the acrylic plate above the projector.

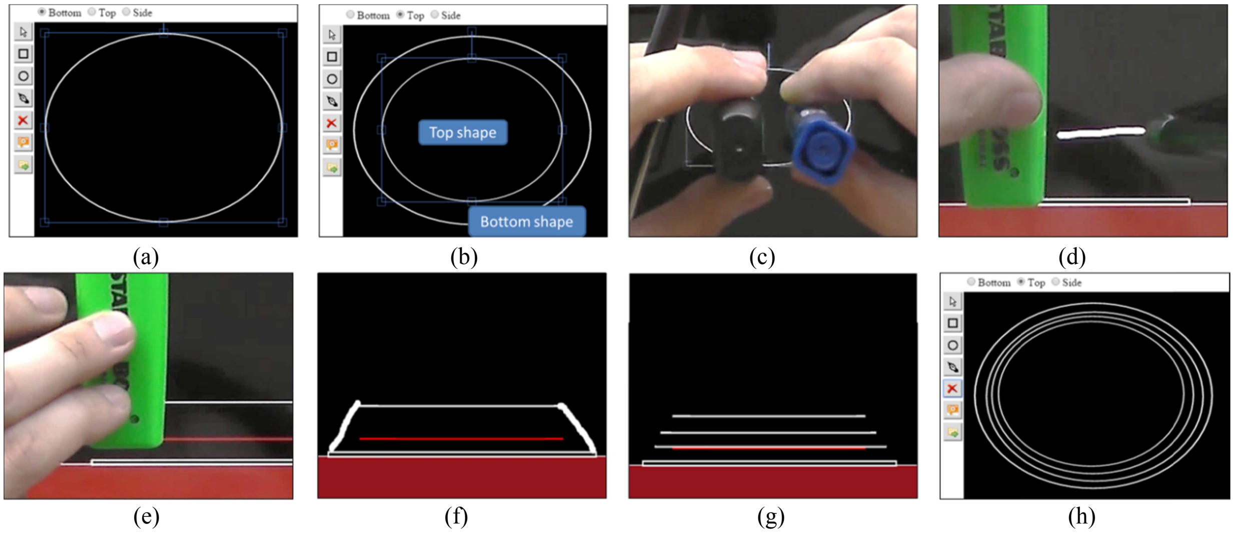


Figure 3: Example of designing a penholder

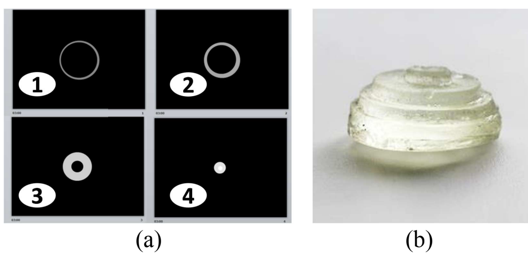


Figure 4: Light patterns to print a half sphere.

The base of the resin was made of flexible silicon, to facilitate easy-removal of the printed shapes. To achieve maximum illumination, the distance between the projector and the resin container is set to be the minimum projection distance of the projector model (22 cm in our setup). The computer is connected to the projector to control the projected images to create objects layer by layer.

To reduce cost and complexity in our first attempt, we did not include the z-axis linear actuators to enable 3D printing typically equipped by existing SLA printers. As a result, the current setup only supports the printing of 2.5D objects. These objects are often greatly preferred for CNC milling and can be used to create a large number of useful parts. In addition, any 3D object can be composed using multiple 2.5D objects, at least in theory.

To print a 2.5D object, one can shine a sequence of slides through a DLP projector to the appropriate region of the resin to cure the resin layer by layer. For example, to print a half sphere (Figure 3b), one can shine the sequence of light patterns in Figure 3a to the resin. To control the thickness of a printed layer, one needs to carefully control the intensity of the light source and duration in which the resin is cured under it. While commercial printers have pre-set values to achieve optimal printing results specific for their printer hardware, the relationship equation for a DIY setting needs to be determined by users themselves. In the section Technical experiment on 2.5D Resin Printing, we describe a simple procedure and a template formula to help hobbyists and researchers derive the mathematical models for their specific setup.

FusePrint Process

The overall process of printing a 2.5D object using FusePrint consists of the following steps (Figure 1): A user first needs to specify the shape of the printed object and its dimension in a modeling software; the system then translates the model into a sequence of images in which each image is a cross-section of a 2.5D model representing a layer of that object needing to be printed. According to the height of the layer, the image is set with different light intensity values. Each image will be shined into the resin for a pre-calculated duration to ensure the printed object has the desirable shape and height.

We designed and implemented a software application for FusePrint which contains a web-based sketch interface allowing users to design the 2.5D patterns on mobile tablets (Figure 2a) and a plug-in for Microsoft PowerPoint to generate projection patterns based on the design of 2.5D shapes. To create a 2.5D model such as a cone, users first need to draw the bottom shape of the object in the canvas of the sketch interface, which supports basic shape drawing and freehand drawing, as shown Figure2a.

In the second step, the user activates the canvas in the top view where our software automatically creates two clones of the design in the bottom view (one for editing and the other for reference). As shown in Figure 4b, the user can resize the top shape with the reference of bottom shape. While editing the shapes in bottom view and top view, users are allowed to use physical objects as reference to assist their shape design. Figure 4c shows a user employing two marker pens to assist him in resizing the shape for a stationary holder, to ensure enough space for stationaries.

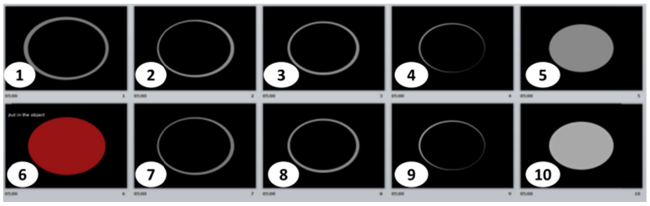


Figure 5: Slides generated by our MS PowerPoint plugin for printing a penholder.

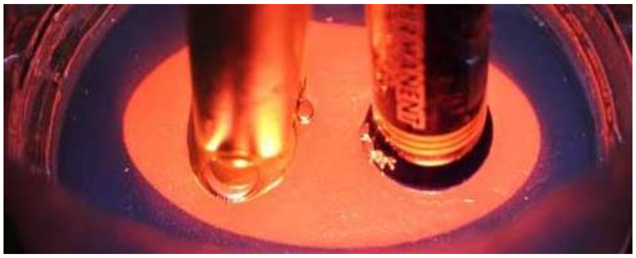
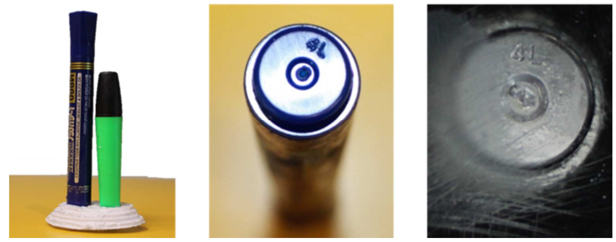


Figure 6: Placing physical pens into the resin during the printing process of a pen holder

After designing the shapes for bottom view and top view, the user can switch to the side view where the interface helps the user to design the height of the printed shape. The user draws two strokes to indicate the bottom and the top of the printed object (Figure 4d), and the software generates two straight lines according to the sizes of the shapes in bottom and top views and the positions of the two strokes made by the user. The vertical distance between the two straight lines indicates the height of the 2.5D object. As shown in Figure 4d, the user can utilize physical objects to help the design of the height.

To facilitate the object placement, the sketch application provides a "Place Objects" button. To specify where to insert an object, the user can toggle the insertion mode by clicking this button and draw a new stroke (in red) between bottom and top lines to indicate the location of the inserted object. As shown in Figure 4e, the user can again utilize physical objects as a reference to indicate the height to place objects (red line indicates the height to place objects). The system will automatically calculate the layer and the time in which the object can be inserted in the printing process. During the printing process, the system pauses the printing and alert the user to insert the object when corresponding layer is reached.

After specifying the information for the height and the object insertion, the user can then design the slopes of the printed object by sketching to connect the bottom and the top lines, as shown in Figure 4f. Lastly, the user clicks the "Export" button, and the system analyzes the design and calculates the number of interval layers that are needed to be printed based on the design of the slope and the height. Our algorithm automatically generates one interval layer in every 2 mm between the bottom and the top lines (Figure 4g) shows the side view of the generated layers and Figure 4h shows the top view). The shape in that layer is scaled according to its distance from the bottom line. The program



(a) (b) (c)

Figure 7: (a) printed pen holder (b) the bottom of a marker pen (c) the texture imprinted on the substrate

then converts the model into a sequence of slides (Figure 5) and automatically sets the duration in which each image will be projected into the resin to form the desirable effect.

To print the object, the user just plays the slides which will be projected into the resin. The red slide in Figure 5 indicates the moment the physical object needs to be inserted by the user. When the slides turn red, the printing process is paused, since the resin would not be cured in red light spectrum. Therefore, the user can place the physical objects in the resin (Figure 6) and continue the printing. The rest of the projection slides continue the printing, and "engrave" detailed patterns on the bottom surface of the object in the printed product, as shown in Figure 7b & 7c.

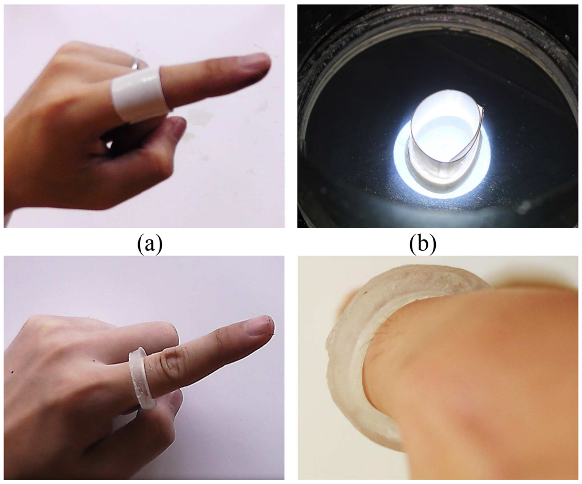
Once the printing process is complete, there are further steps to follow to post-process the printed result. The post-processing stage (Figure 2c) contains a washing container, UV light box, and sand paper. Similar to post-processing in SLA 3D printing, the user gently peels the model off the container base, washes off the remaining liquid resin on the model surface, applies UV exposure by putting the printed part in the box with a 30W UV light tube for 3 minutes, and finally sands the surface of the model to achieve the best surface result.

A 30W UV light tube can be easily for less than ten dollars from Amazon. Figure 7a shows the final product of the penholder using the generated images in Figure 5.

Additional Usage Scenario

Depending on various needs, one can place the physical object at different stages of the printing process to create different effects. When the physical object is placed at the beginning of the printing process, it will result in a hole fitting the object's contour in the final printed product. Holes can also be formed by embedding a mold of the real-life object in the resin. For example, one could create a mold of his/her finger with paper/plastics/clay (which are highly accessible) and place the mold in the resin, creating a well-fitting ring (Figure 8). The close-up view in Figure 8d specifically shows that there is little space between the ring and the finger, indicating a good fit.

Another interesting application of FusePrint is the ability for users to place screws in the liquid resin (Figure 9a), so the resin can be cured around the screw, and create internal threads that tightly fit the particular type of screws without



(a) (b) (c) (d)

Figure 8: (a) user made a model of the finger using a plastic wrapper (b) the plastic wrapper is placed in the resin during printing (c) the printed ring fits nicely to the finger (d) top down view of the ring.

(a) (b)

Figure 9: Print a screw thread (a) a physical screw is placed in the resin to create the internal structure for a thread (b) the screw can tightly fit into the thread

measuring and modeling (Figure 9b). By mixing the photo-reactive resin and conductive gel, we can create conductive objects that can be used as capacitance-based touch sensors, as shown in Figure 10. Different shapes resulted in different conductivities and further achieved different touching sensitivities; thus a unique touch ID can be assigned a particular object. In addition, the printed parts can detect the number of touch points, facilitating the design of multi-touch interaction.

TECHNICAL EXPERIMENT ON 2.5D RESIN PRINTING

To investigate the feasibility of DLP-based 2.5D printing, we experimented on how the length of light exposure and the color of the projected pattern could affect the thickness of the printed object. In the first trial set, we fixed the depth of the liquid resin at 2.5cm. We varied the RGB value of the projected color from gray (127, 127, 127) to white (255, 255, 255). The resin was exposed in light projection with 4 different durations: 3 minutes, 5 minutes, 10 minutes, and 15 minutes. We collected 28 data in total.

Experiment Results

As shown in Figure 11, the height of the printed object has a positive correlation with the RGB value of the projected

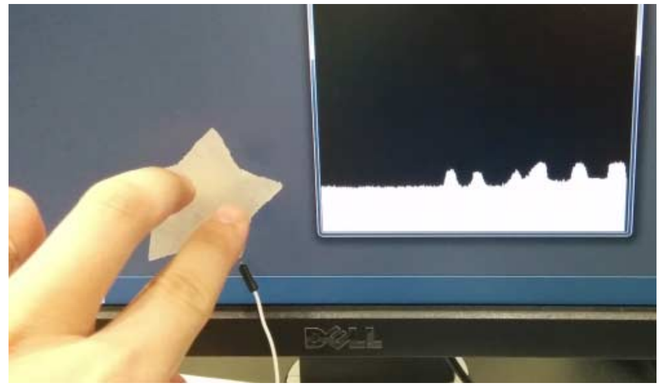


Figure 10: Print a touch sensor with the mixture of photo-reactive resin and conductive gel.

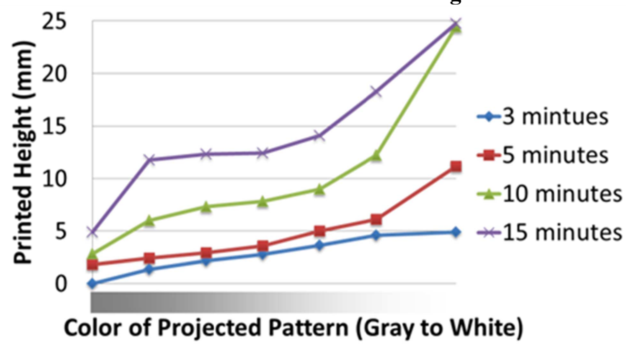


Figure 11: Experiment data on the effect of projection color and time on the height of printed objects.

color. With the same projection color, the height increases along with the increment of the length of light exposure.

We further fitted these experimental data into a multivariate 3-degree polynomial model (Equation 1) to predict the height of the printed object (h) with a particular setting of the grayness of projected color (c) and duration (t). Based on the relationship among printed height, projected duration, and projected color, as shown in Equation 1, the PowerPoint plug-in computes the color of the object and the advance timing of the slides given the height specified by the user in the sketch interface. Noted that Equation 1 was derived from the empirical data collected using the setup specification described in FusePrint Setup section, thus the factors might change if the set-up is modified. With this consideration, we designed the PowerPoint plug-in to allow researchers to input their own experimental data and derive the suitable multivariate polynomial equation.

$$h = -0.00280t^3 - 0.00125t^2c + 0.0000477tc^2 + 0.000167c^3 + 0.300t^2 + 0.0125tc - 0.00941c^2 - 3.53t + 1.66c - 90.6$$

$$Residual\ Sum\ of\ Square: rss = 9.91$$

$h\ (mm)$: $height\ of\ the\ printed\ model$

$t\ (minute)$: $length\ of\ light\ exposure$

c: $grayness\ of\ the\ projected\ color\ (setting\ the\ RGB\ values\ equally)$

Equation 1: Polynomial model of the effect of projection color (c) and time (t) on the printed height (h).

Time (minute)	Calculated Color (R, G, B)	Designed Height (mm)	Printed Height (mm)	Error (mm)
10	(152,152,152)	6	5.93	0.07
5	(249,249,249)	10	9.35	0.65
15	(212,212,212)	15	14.23	0.77
8	(252,252,252)	17	17.66	0.66
12	(255,255,255)	24	24.42	0.42

Table 1: Validation of Equation 1

Validation of Mathematical Model for 2.5D Printing

We performed a validation experiment to test our mathematical model and the PowerPoint plug-in for 2.5D resin printing. We randomly picked 5 combinations of printed height and time and employed the plug-in to generate 5 different slides, which were projected into the resin individually. We measured the heights of the printed objects and calculated the error between the printed height and the designed height. As shown in Table 1, the printing process achieved marginally low errors (rss = 1.63) between the designed height and printed height, which validated our polynomial model in Equation 1.

Mixing Resin with Conductive Gel

We experimented with the conductivity (electric resistance) of a mixture of resin and conductive gel, in which conductive gel has been widely used in cosmetic and medical treatments. We identified two factors that affect the conductivity of the printed objects: the ratio of conductive gel and photo-reactive resin, and the shape of the object. Figure 12 illustrates the resistance change in printed objects produced with 5-mintute projection exposure. These objects had different shapes (an equilateral triangle with edge length of 5cm, a rectangle sizing 4cm x 3cm, and a full circle with diameter of 5cm) and a different ratio of mixture. We can see a significant reduction in the electric resistance along with the increase in proportion of the conductive gel in the mixture, and the resistance varies among three different shapes.

Our results (demonstrated in Figure 12) further suggested that printed resistance varies significantly among different shapes under the ratio of 1:3 and 1:2 (Gel:Resin). In addition, the printed electric resistance could easily achieve the insulating level (>10Mohm) using 1:3 mixture. Also, the surface roughness increases along with the increment of the conductive gel in the mixture, as the mixture with more conductive gel has stronger effect on light scattering. Thus we decided to carry on the rest of the experiments with the 1:2 mixture of conductive gel and photo-reactive resin.

Making Different Touch Sensors

The various electric resistances can provide interactivity to these SLA-3D-printed objects, and objects with different resistances can be created in different shapes.

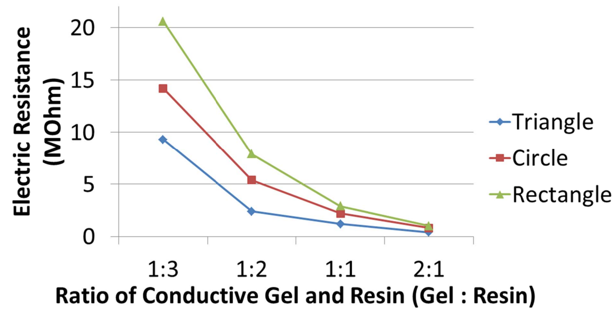


Figure 12: Experiment data on the effect of mixture ratio and printed shape on the conductivity of printed objects.

Figure 13: Printed touch sensors in different shapes.

The conductive objects can be connected to the normal capacitive touch-sensing circuit to form touch sensor circuits, as shown in Figure 13.

WORKSHOP STUDY

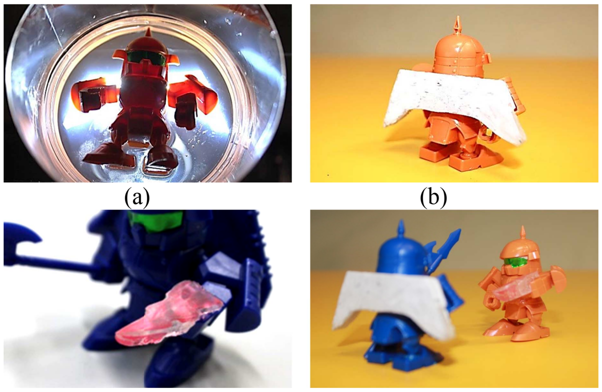
To further understand how FusePrint could be used in the process of design and rapid prototyping, we conducted a series of empirical workshops by inviting users with different backgrounds to use the FusePrint process. We adopted the evaluation strategy followed by other creative systems [17, 25], and procedures used by Buechley et al. [5] in electronic textile for our evaluation.

Workshop Participants

Our workshops had a total 8 participants (one participant per workshop), consisting of five males and three females with ages ranging from 20 to 32 years (M=23.25, SD=2.11). Prior to conducting the workshops, we collected the participant's background information in 3D printing. Two participants self-rated as experts, four self-rated as beginners, and two had never tried 3D printing before.

Workshop Apparatus

The workshops were held in a fabrication lab (10 m x 7 m) in a local school, with various prototyping tools, such as screws, screwdrivers, drillers, etc. Each participant worked with a FusePrint setup: an iPad 2 and a stylus in the design stage; a MacBook Pro connected to Optoma DLP projector EH1060, and a resin container with 500g resin (Form1



(a) (b) (c) (d)

Figure 14: Printing new parts for toys.

Clear) in the printing stage; two pairs of tweezers, 100 ml of ethyl alcohol in a bottle for cleaning, one UV light box with 30W UV light tube, and 3M #600 sandpaper in the post-processing stage. In addition, we provided several everyday objects, such as stationaries, water bottles, plastic toys, etc. Participants were also allowed to bring their own objects to the workshop.

Workshop Procedure

The workshop was conducted in four sessions:

1. Introduction (20 minutes). The workshop facilitator gave a brief introduction of FusePrint and the technology of SLA 3D printing, and showed a few examples of printed outcomes. The objective was to give the participants a brief understanding of the system and the technology. The participants were allowed to ask questions at any time during the introduction.

2. Guided Task (30 minutes). After being introduced to FusePrint, the participants were given a tutorial on how to use FusePrint to make a ring that matched his/her finger. The participants were asked to recreate this example to familiarize with the fabrication process. The activity included creating the wrapping that fit the finger, designing the shape of the ring, printing the ring with the wrapping, post-processing the printed result.

3. Free Task (30–40 minutes). Participants were encouraged to freely explore their own imagination by using physical objects in FusePrint. They were allowed to use any objects in the workshop space. This session was to provide insights on how FusePrint allowed users to explore their creativity.

4. Demo (10 minutes). After finishing the free task, each participant was asked to show his/her result to the workshop facilitator, and explain the design rationale.

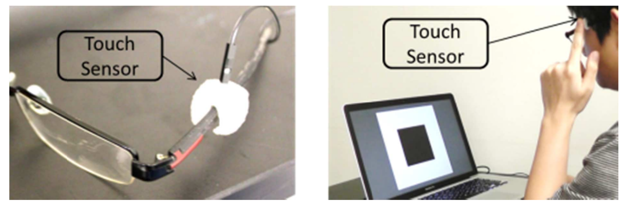
The workshop process was video recorded with the participants' consent. After the workshop, the participants answered a questionnaire on their impressions of FusePrint.

Workshop Outcomes

We summarized the objects printed by the workshop participants into three main themes: *making accessories for physical objects*, *adding interactivity to physical objects*, and *fitting details of physical objects*. We will discuss these three themes by using the representative examples created in the workshops.

(a) (b)

Figure 15: Printing a stand fitting the shape of the phone.



(a) (b)

Figure 16: A printed conductive accessory for the glasses.

Making Accessories for Physical Objects

While printing screw thread focuses on the more industrial-oriented application of FusePrint, the workshop results of making new parts for toys suggested the application towards personal entertainment. There were two new toy parts created in the workshops. In these two examples, existing parts of the toy (hand and body) were placed in the resin (Figure 14a), so the printed new parts could fit into the slots in the original parts (Figure 14b and 14c). As the two toys were manufactured from the same company with the same standard, the new parts could be swapped between two toys to create new combinations (Figure 14d).

One female participant (28 years old) created a new stand for her mobile phone. She drew the shape of the stand by tracing the edge of her mobile (Figure 15a) to make sure the slot fit the size of the device well (Figure 15b).

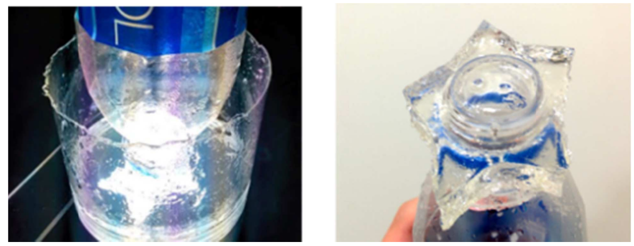
Adding Interactivity to Physical Objects

One interaction designer (final-year undergraduate majoring in art and interaction design with 3 years of experience in Processing and Arduino) created a tiny accessory for his glasses using the mixture of photo-reactive resin and conductive gel, turning his glasses into a pair with touch-sensitive capabilities. Using a plastic sheet wrapped around the earpiece of the glasses, he printed the Touch sensor that could be easily and firmly attached to his glasses (Figure 16a), and quickly developed an interactive demo, as shown in Figure 16b.

He commented that the functionality of using a physical object to shape the printed part that fit back onto the object could shorten the iteration of prototyping for designers. In theory, they could quickly create a nice proof of concept in the first iteration, as they would be able to focus more on

(a) (b) (c)

Figure 17: A screw-assembled hanging hook made in the workshop



(a) (b)

Figure 18: Customized bottle cap made in the workshop

the functionality of the design instead of the tedious modeling and printing process.

Fitting Details of Physical Objects

The most common usage of FusePrint is to fit detailed parts of physical objects. One 31-year-old male participant, who is a mechanical engineer, created multiple parts with M4 screw threads and assembled them together with screws (Figure 17a). He screwed the assembled structure into an existing hole in the wall (Figure 17b) and created a hook for hanging clothes (Figure 17c). He commented that FusePrint would be very useful in creating tiny parts for home appliances to fit with original parts, especially those easy-to-lose-but-not-easy-to-buy-new ones, such as special screws and screw bolts. He said it would be time saving and cost saving to set up FusePrint at home and make parts whenever he wants.

Another example was one customized bottle cap (Figure 18) created by one 28-year-old female participant. She mentioned that sometimes she wants to re-use plastic bottles, and she could use FusePrint to personalize these bottles to differentiate from others. She also suggested that she could use this technique to create different caps for medicine bottles for her vision-impaired grandmother.

Quantitative and Qualitative Results

Intuitiveness and Learnability

Participants found the software interface and the process of placing physical objects easy to learn and intuitive. They commented that the idea of directly placing objects in liquid resin is "*intuitive.*" One participant said, "*using physical objects [as reference] to design the printed shape is very similar to what I usually did in quick sketch design.*" The quantitative result of *learnability of designing shapes to print* received an average score of 4.25/5. All of the participants were able to follow the tutorial to create well-fitting rings within 30 minutes. In the free task, they were able to generate various ideas and create new objects with everyday physical objects.

On the other hand, the participants' comments identified the potential problems with the sketching interface. Questions like "*Can I combine different shapes to create new shapes?*" and "*Where exactly should I put the object in the red circle?*" indicated improvement could be done in the shape design and the indication of the spot for object insertion.

Usefulness and Engagement

The participants agreed that the process of directly placing physical objects as molds is useful and suggested the application in: mechanical fabrication, toy design, wearable design, interactive system prototyping, etc. One participant suggested, "*FusePrint would make it easy for disabled people to make a DIY prosthesis that perfectly fit their bodies,*" which indicates a potential application in biomechanics and healthcare.

The average rating for engagement was 4.5/5. One experienced 3D-print practitioner commented: "*I felt more close to my printed product in this process than 3D printing, because here the printing time is shorter, and you can get involved during the printing, but in 3D printing, you can do nothing but just watch and wait once pressing the start button.*" In addition, participants felt the process was more fun when given the freedom to explore different possibilities with different objects, than the guided task.

DISCUSSION

Comparison with Other Methods

We compared FusePrint with existing methods in terms of cost, time estimated for fabricating the pen holder (described in FusePrint Process section), printing technologies, products, types of inserted artefact, the modeling process, and the requirement of tolerance adjustment in the hardware, as shown in Table 2. FusePrint offers acceptable cost, and allows intuitive sketch-based modeling of the connection, instead of requiring accurate scanning/modeling tools. The comparison on time spent for fabricating the described pen eliminated the time for measuring and modeling, and showed that the SLA-based FusePrint outperformed the FDM/SDM-based techniques which could suffer from fabricating objects with large sizes. While the existing FDM/SDM-based methods required the ad-hoc tolerance adjustment on hardware, the nature of light-based fabrication in FusePrint eliminates this tedious process. In addition, FusePrint adopted the SLA technology, a different approach with the existing methods, which we hope can potentially open up future opportunities for innovation in the area of rapid prototyping.

On the other hand, it may be possible to conduct the experiment of FusePrint with existing commercially-available DLP-projection-based 3D printers (i.e. Kudo3D Titan 1 [4] and B9 Creator [2]), but modifying the infrastructure (i.e. removing the moving mechanics above

	FusePrint	Encore [32]	Voxel8 [31]	Printed Optics [16]
Cost	~$650	~$350	~$550	~$20,000
Time spent for fabricating the pen holder	~20 min with the described settings	~45 min with MakerBot Reprecator 2 [22]	~45 min with MakerBot Reprecator 2 [22]	~50 min with Objet Eden260V [23]
Printing Technology	SLA	FDM	FDM	SDM
Printed Object	2.5D	3D	3D	3D
Inserted Artefact	Physical objects & liquid	3D printed objects with the same material	Electronics	Electronics
Physical Connection Modeling	Sketch-based modeling on tablet	High-end accurate scanning/modeling for surface connection		
Tolerance Adjustment	Not required	Require ad-hoc adjustment.		

Table 2: Comparison of FusePrint and existing methods for embracing physical objects in fabrication

the resin) and tuning the parameters (i.e. adjusting the projection) of these commercial printers could be non-trivial without detailed technical specification from the companies. In addition, there emerged more related literature on customizing DLP-projection-based 3D printers in the maker community than the commercial market. Thus, it was more cost-and-time-effective for us to customize our own projection setup for FusePrint than purchasing and modifying commercial product. Lastly, FusePrint may seem similar with clay molding at the first glance, but FusePrint offers the possibility for setting up in the daily environment with off-the-shelf DLP projectors, while clay molding usually requires advanced manufacturing skills and facilities, such as cutters and high-temperature ovens.

Limitation

Ease of Setup

The participants in the presented workshop studies were not asked to set up the FusePrint system from scratch, thus the ease of setup for FusePrint was not evaluated explicitly. However, one participant mentioned it would be time saving and cost saving to set up FusePrint at home. As one future plan, we will investigate the set-up and the usage of FusePrint in different settings, including home, school fablabs, and maker spaces. Particularly, we would like to investigate the ease for makers and hobbyists to replicate the DIY process of collecting empirical data, tuning the polynomial factors, setting up and using the FusePrint system.

3D Fabrication

Our experiment showed that FusePrint is enable to fabricate high-precision assembly mechanisms, including non-permanent assembly (i.e. screw threads, which is essential in valve structure) and permanent assembly (i.e. shaft-hole sockets and pipes), without requiring high-end modeling tools. However, the current setup of FusePrint has limitations that prevent it from fabricating complex structures, such as hollow or suspension structures. As the next step, we will explore how to fabricate true 3D objects with FusePrint, by carefully calibrating and coordinating the top and the bottom projection. One other solution is to parse the 3D models into multiple 2.5D parts, and print them in sequence where the printed part can be inserted for fabricating new parts, so that they can be assembled into 3D.

While the current FusePrint can produce user-acceptable 2.5D objects, shape distortion may occur when printing different heights in the z axis. This is mainly due to the difficulty of controlling light transmission in the liquid resin. Lastly, users are required to use gloves while handling the photo-reactive resin because touching the liquid resin can "*cause mild skin irritation for some people*" [12].

CONCLUSION

In this paper, we introduced FusePrint, a DIY 2.5D printing technique exploring the possibility of inserting everyday artifacts in SLA-based 2.5D printing. We experimented with how lighting condition affected the height of a printed object, derived a mathematical model, and applied it to the software part of FusePrint. We also explored the possibilities of inserting physical objects and conductive gel into the printing process. The workshops on FusePrint suggest the technique is easy to adapt for making objects that fit well with existing ones, and users are highly engaged in the printing process. More importantly, the workshops revealed various possible applications of FusePrint: mechanical fabrication, toy design, wearable accessories, rapid prototyping for interactive system, bioengineering, etc.

For the future work, we will further investigate the setup and the usage of FusePrint in different contexts. Finally, this fabrication process points to further investigation, including integrating with traditional moulding technique, fabricating true 3D objects, mixing different materials, and empirical investigations of resulting characteristics (e.g., conductance, color, texture, and haptic properties).

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