3D Pen + 3D Printer : Exploring the Role of Humans and Fabrication Machines in Creative Making

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ABSTRACT

The emergence of a 3D pen brings 3D modeling from a screen-based computer-aided design (CAD) system and 3D printing to direct and rapid crafting by 3D doodling. However, 3D doodling remains challenging, requiring craft skills to rapidly express an idea, which is critical in creative making. We explore a new process of 3D modeling using 3D pen + 3D printer. Our pilot study shows that users need support to reduce the number of non-creative tasks to explore a wide design strategy. With the opportunity to invent a new 3D modeling process that needs to incorporate both a pen and printer, we propose techniques and a system that empower users to print while doodling to focus on creative exploration. Our user study shows that users can create diverse 3D models using a pen and printer. We discuss the roles of the human and fabrication machine for the future of fabrication.

CCS CONCEPTS

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

KEYWORDS

Digital fabrication, 3D pen, 3D printer, creativity

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1 INTRODUCTION

With the rise of personal fabrication and affordable digital fabrication machines [3, 24], CAD tools and creativity support [34] have become challenging themes in the HCI field. Despite advances in 3D printing, users' creative activities for creating 3D objects have been limited. To lower the entry barrier for users, most general-purpose CAD tools have users work from shape primitives or spline systems, which unwillingly induce a procedural process.

At present, commodity 3D pens are largely available. A hand-held 3D printer allows users to directly manipulate 3D shapes on-the-fly without any digital 3D models ready for processing and to modify the modeling process as they make things using craft materials. Nonetheless, 3D doodling also remains a challenging task and requires craft skills to construct a plausible 3D shape. Existing studies propose the use of stencils [1] or mixed-reality guides [45], thereby leaving space for CAD at some points. We aim to extend these studies to the next step and enable users to directly manipulate 3D objects in the creation process.

In this paper, we discuss the challenges and opportunities for creative activities using a 3D pen and examine what type of making experiences can be realized to empower users to explore creative making with 3D printing. Currently, a 3D creation bipolarizes modeling into a screen-based design and a challenging but creative hands-on activity. Our motivation is to explore the capability of *3D pen + 3D printer* around a human's creative activity to encourage the use of a 3D pen in modeling.

Our key contributions are three-fold:

- Identification of the key factors in creative making with a pilot study of general 3D pen tasks. Introduction of a 3D printer into 3D doodling as a tool to facilitate creativity.
- Seven design techniques to facilitate creative making experiences using pen + printer. Workflows with a 3D printer setting and a system that allows users to print simple shapes that can serve as scaffolding for creations.
- A user study that shows a new opportunity for using pen + printer in creative making. A variety of craft techniques and strategies that involve the use of a 3D pen and 3D printer in creative ways.

2 RELATED WORK

Our work is inspired by personal fabrication with a focus on supporting hand work using digital fabrication technologies by investigating the unique roles of these two participants.

Personal & Digital fabrication

Recent research on personal and digital fabrication moved the focus to improve efficiency and interactivity in the design process [5, 8–10, 25, 26, 28, 37]. With the concept of interactive fabrication [43], recent advances in this domain have facilitated the real-time input for fabricating physical forms and allowed humans to directly manipulate machines throughout their processes [27, 29, 30, 41, 44]. The basis of our work originates from this lineage of work in facilitating direct manipulation and interactive fabrication by exploring a new type of personal fabrication to present unique workflows by combining digital fabrication and craftsmanship.

Support for Hand Work by Digital Fabrication

Hand-held craft tools offer a hands-on fabrication experience and support quick exploration [49]. D-coil [31] and FreeD [47] add intelligence to a device and assist designers with haptic feedback according to a design input. ExoSkin [15] helps on-body fabrication using a human body as a canvas to explore hybrid fabrication workflows. SPATA [40] is a smart tool that enables a designer to measure and transfer a physical dimension to synchronize hand work the digital design. WeaveMesh [36] is a prototyping system that produces objects in a mesh structure inspired by the craft of hand weaving. Using clay and printed widgets, “What you sculpt is what you get”[19] allows a designer to make interactive devices without requiring skill in a CAD system. 3D pens, one type of hand-held device, still require support [45]. We identify the key factors in creative making with general 3D tasks and introduce a 3D printer to 3D doodling as a support tool to facilitate making.

Collaborative Digital Fabrication

Collaborative and social fabrication has provided a promising future for fabrication [3]. The latest work proposes machines to be used as a tool *during* creative works, not simply as the final output appliance. For humans to collaborate with machines as co-designers, machines should be thought of as live collaborators and agents to aid in-situ creativity [20]. Similary, compositional 3D printing [22] recasts a fabrication process to enable users to compose a 3D model via real-time design decisions and expressions. Hybrid fabrication is the vision of integrating digital fabrication techniques with analog craft practice to extend traditional craft. Hybrid artisans [48] have examined the value added to traditional craft practices. To facilitate both high-fidelity crafting and interaction with materials, Proxyprint [39] and MixFab [42] invite users to bring existing objects and materials to a digital design space. Being the Machine [14] proposes machines as guides for users to reconfigure agency and control in hybrid fabrication. However, collaborative fabrication systems lack support for users while making as needed during the process. We adapt previous work to promote collaboration between machines and humans [7] but in an advanced manner to facilitate more creative ways of 3D creations.

3 3D PEN + 3D PRINTER

Motivation and Goal of 3D Creation

For a pilot study, we first suppose three types of motivation and strategies of 3D creation while comparing the role of hand work using a 3D pen with 3D printing.

(A) With a concrete goal, making with high fidelity
Proceeding toward a clear goal is one creative experience [12]. In this motivation, users may expect an outcome with high fidelity and expressiveness. If there is a 3D model as a goal and users have sufficient knowledge, that will be the goal. In creative making using pen + printer, for example, a 3D printer can contribute to users by accurately printing complex shapes, smooth surfaces, and almost anything with fidelity with regard to the physical properties such as size, symmetry, and proportion.

(B) Deciding what to make while making
This is similar to many creative activities in which humans explore what to create and how to create while actually making it. Like sketching in the early stage of creation [6], a 3D pen also welcomes this type of motivation. It is important for users to rapidly explore various possibilities and engage in creation. A 3D printer may not work well at this stage because it requires a 3D model, but it can be used as a tool to explore or partially create a goal. For example, a user who wants to create any animal (but has not decided which animal) can print a snowman-like shape as a scaffold for 3D doodling and can explore by adding ears, limbs, and a tail.

(C) Without a goal, just making, playing, and learning
A 3D pen allows users to manipulate shapes without any digital 3D models; therefore, users can start making without a goal. Users can not only explore but also positively engage in the activity and enjoy it. Hopefully, an understanding of materials will be cultivated through work [14]; serendipity due to manual uncertainty will be added to the work. To clarify a goal, a 3D printer can contribute by printing examples or almost completed objects; these allow users to explore and easily reach a goal.

Pilot Study: User’s Goal Setting and Reaching

Taking into account the three premises, we conducted two pilot studies to understand how users handle a 3D pen, what

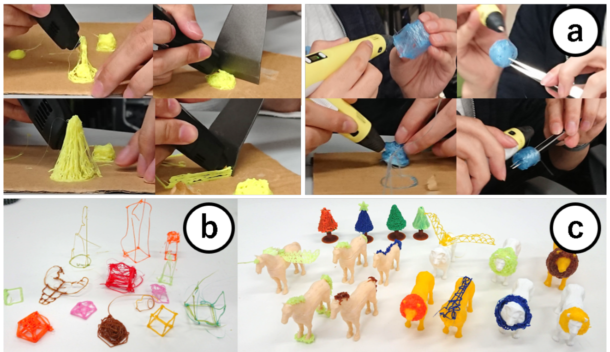


Figure 1: Pilot study. (a) Two participants attempt to doodle simple primitives. (b) Some high school students try wire drawing. (c) Students doodle with 3D printed objects.

difficulties they may face, and what opportunities are available for new types of 3D creation processes. The purpose of the study is observational; we recruited two graduate students from the lab and a group of casual users including some high school students regardless of their prior experience. We only explained how to use 3D pens and let them freely work without any restrictions. We prepared 3D pens, craft tools, and example objects. To save time for 3D printing during the pilot study, we prepared preprinted craft scaffolds.

We instructed the two participants with no experience with 3D doodling to make simple primitives using a 3D pen and craft tools for an hour (Figure 1a). We let them make solid shape objects and provided example objects, so that the participants can have a concrete goal to achieve (A). Similarly, we asked the casual users to use a 3D pen without providing specific instructions. Some participants seemed to have a vague goal (B), and they stated what they would try to create, e.g., a wireframe box, a cylinder, and their own name (Figure 1b). Some participants who started to doodle without saying anything seemed to not have any goals (C).

We observed that the participants enjoyed doodling, and various ideas were rapidly physicalized. They exploited craft tools in various ways to leverage creations (Figure 1a); one participant used a spatula as a wall to support doodling, while another used a tweezer as a spindle to wind material. The casual users also engaged in 3D doodling, and some of them compared the 3D pen to a glue gun. However, they were unable to doodle even simple primitives or created unstable wire shapes, as reported in [45].

Towards Creative Making with Pen + Printer

We found that a 3D pen allows users (1) to directly manipulate material and experience rapid physical making, often (2) letting users enjoy the process— critical factors for creative exploration. Similar to crafting, humans can have more control of the object, even without concrete goals at the beginning. However, without proper support, users may have difficulties reaching the goal of making, and the variety could be also limited (Figure 2a). Inevitably, human skills lack precision and speed. With the rise of 3D doodling, stencils have been provided by designers to support beginners [1]. Users only need to follow fixed lines in 2D, transform it, and assemble an object into a 3D shape. If they weld parts, somewhat sophisticated objects can be created (Figure 2b). Skilled users often utilize craft materials; for example, crumpled paper can be used as a scaffold to obtain a global shape (Figure 2c). Users can then be more concerned about other factors to enrich their design: color, texture, size, and more. Thus, users can improvise further and create personalized objects. It is important for users to understand how to distribute a load associated with a creative activity [13].

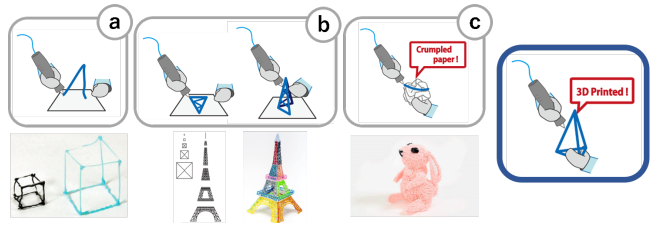


Figure 2: 3D doodling techniques: (a) conventional wire drawing, (b) doodling using stencils, and (c) doodling using a foreign item. We consider doodling with a printed object.

We envision offloading non-creative work to a 3D printer. Figure 1c shows the creations made by the participants. We provided printed objects such as animals, a tree, and a nameplate, and the users decorated them using a 3D pen. They were able to create varieties that are unique to each other by only stroking the surface of the object. As observed in [39], users can be at the correct stage where they need their own creativity. The power of a 3D printer, however, may deprive the user of serendipity, ownership, a sense of accomplishment in 3D doodling. With these motivations, we introduce and demonstrate design techniques and present a system that allows users to 3D print what they can use during creation while doodling their 3D objects.

4 DESIGN TECHNIQUES: DOODLING + PRINTING

In this section, we introduce seven design techniques that innovate the 3D modeling process using a 3D pen and 3D printer. We first categorized the keywords found from the pilot study observations of users' behaviors, previous works, and collected use cases including 3D doodler's how-to videos, art works showcased on Pinterest, and YouTube videos.[1] We subsequently derived categories for these techniques.

Technique 1: Adding details to a 3D printed body

As observed in the pilot study, even creating a simple primitive could be challenging. In this case, users can benefit from

[1]We gathered contents with queries such as 3D pen and 3D doodling

Figure 3: 3D doodling on 3D printed objects. (a) Users can produce works by stroking the surface or (b) filling wire-frame structures using a 3D pen.

precise 3D printed scaffolds that operate as guides for novice users. Complex shapes such as animal bodies can also be printed for 3D doodled details (Figure 3a). Users can easily reach their concrete goal, being able to care only about details or addenda (i.e., the surfaces of soccer balls, the leaves on trees, and the hairs on animals). However, the users' space of creative exploration is limited, as they may largely rely on a global shape. For example, creating a giraffe from a lion would be nearly at impossible, while adding lion hairs to decorate the animal figurine is relatively easy to accomplish.

Technique 2: 3D printed wireframes for global shapes

Wireframe structures have been used to improve the printing speed [26] and rapidly fabricate mesh models [23]. Using wireframes, users can obtain a global concept of a work as observed in many craft practices such as sculpting and large-scale architectures, and construct a new creation that can be called "3D coloring" (Figure 3b[2]). Wireframes have open surface and uncontrollable areas (on an edge or a facet). Handling imperfections promotes users' understanding of materials, facilitating their learning from their progress and allowing them to become even more skillful [46].

Technique 3: Expressing textures

Texture is an important factor that is related to human tactile perception, as researched in various ways in the digital fabrication domain [18, 38]. Although expressing fine textures with a 3D pen is fairly limited, a unique surface can be created by the behaviors of the pen tip. This nuance is comparable with smooth 3D printed textures. Figure 4 shows a variety of texture expressions: a bumpy 3D model using a surface processing function in modeling software, expressive fused deposition modeling (FDM) with printing parameter control [35], and the fuzzy skin option of Cura (Ultimaker[3]).

Technique 4: Integrating material properties

Recently, there has been great advances in various materials

[2]These 3D models are made using Meshmixer
[3]https://ultimaker.com/

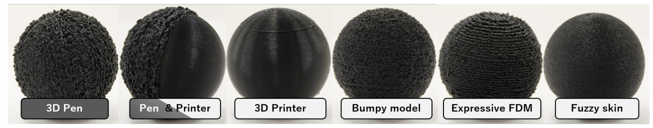


Figure 4: Comparison of textures made with a 3D pen, a 3D printer, and 3D printing techniques.

such as flexible, conductive, water-soluble filaments, which are available for 3D printing. These can be also fed into a 3D pen to quickly and easily switch to introduce unique materiality, as demonstrated in making interactive objects [33]. Figure 5 shows examples of doodling with a conductive material and doodling on a scaffold printed with a water-soluble material; the scaffold part can be removed after making.

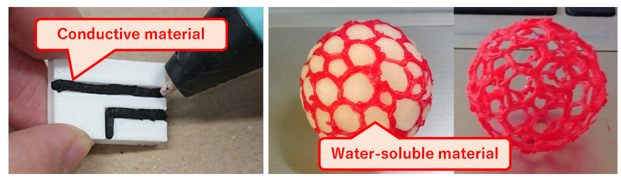


Figure 5: 3D doodling with various materials: doodling conductive wires on the printed dented lines and creating wireframes with a printed soluble scaffold with Voronoi guides.

Technique 5: Doodling with printed on-demand tools

From the pilot study, we observed that participants employed various craft tools. As Mobile Fabrication [32] demonstrated, a 3D printer can make on-demand tools that contribute to physical making using a 3D pen. Printing an on-demand tool is a collaboration between the pen and the printer. In the case where a user needs a tool, they can print one immediately to help their own creation. Figure 6 shows a printed tweezer and a manipulator added at the head of a printed scaffold.

Figure 6: 3D doodling with 3D printed on-demand tools.

Technique 6: Transforming planar figures to 3D shapes

With the thermoformable characteristic of materials, a printed 2D form can be folded into a 3D shape post-printing [2, 16]. Figure 7a shows the development of a box and a leaf deformed using a heat gun. The edges of the box and the veins of the leaf are printed in PLA, while the other surfaces are doodled in ABS. As ABS softens at higher degrees than PLA, heat allows the user to selectively deform the parts printed in PLA. The leaf object particularly benefits from users' fine tuning by hand, as such natural curves are otherwise difficult to express solely by 3D printing.

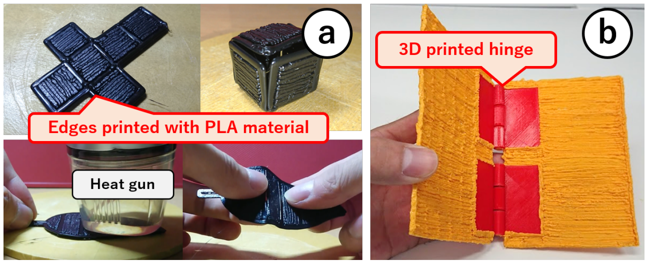


Figure 7: (a) 3D object post-deformed by heat and (b) functional objects created by combining 3D printed functional primitives attached to a 3D doodled addendum.

Technique 7: Making with functional primitives

As demonstrated by 3D printed movable primitives [21], the accuracy of a 3D printer helps create various functional objects such as a screw, hinge, spring, and matching bolt-nut pair. Although the mechanism of these parts is simple, it is difficult to design such functionality with a 3D pen. Figure 7b shows the combination of a printed hinge with 3D doodling.

5 WORKFLOWS: PRINTING IN DOODLING

We detail a 3D printer setting and support system, aiming to improve traditional 3D modeling to aid 3D doodling. In the pilot study, the craft scaffolds used by the participants were preprinted. We implemented a system to use a 3D printer during 3D doodling and to support 3D printing tasks suggested by our design techniques.

Implementation

As shown in [25], increasing the speed is important to tightly engage users. With slicer settings, the system improves the speed and enables users to print stencils and scaffolds for doodling. While 3D printing, a user can concentrate on hands-on creation and then assemble printed parts or rework it to add more details using the design techniques.

3D Printer and Slicer Setting. We used a 3D printer, which is a traditional FDM (HICTOP Portable 3D printer), to implement our system. To increase the printing speed, the nozzle diameter was changed from 0.4 mm to 0.8 mm, extruding a thick stroke. This improves the printing speed with a higher layer height. Figure 8 shows examples of printing with a 0.8-mm-diameter nozzle. This setup allows a Stanford bunny

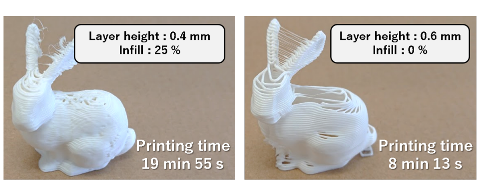


Figure 8: Comparison of the printing time with a 0.8-mm-diameter nozzle.

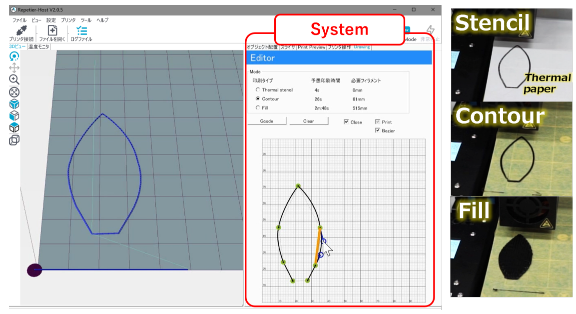


Figure 9: System for controlling a 3D printer. The system allows users to print a 2D shape with three printing styles.

model to be printed in 19 min 55 s with a 0.4-mm layer height and 25% infill density. By removing the infill structure and setting the layer height to 0.6 mm, the bunny model can be printed in 8 min 13 s. The printed results are low-fidelity; however, these are sufficient for use with 3D doodling because users can obtain an abstract scaffold.

System. The system is implemented with C# as a plugin for Repetier-Host[4] and is loaded when this application starts (Figure 9). The system shows a canvas on which users can draw printing paths. A point is added by double-clicking within the blank space or on an edge (the edge is then divided into two edges). All points are draggable and can be deleted by double-clicking again. Each edge has two properties that can be set with check boxes: whether or not material is extruded or not while moving along an edge and whether or not the edge is a Bezier curve (two handles are shown).

The Printing paths drawn by users are converted into Gcode in real time and previewed in a 3D view of Repetier-Host. Information on the printing time and the amount of material for each style are always shown by the system. Note that this Gcode includes additional commands for stable printing. This Gcode is printable with three types of styles: stencil (with thermal paper), contour, and fill (Figure 9, right).

Example Workflows

We present two example workflows here. We used PLA and thermal paper for facsimile, and the printing temperature of the 3D printer and 3D pen was set to 190 °C.

A tree branch with leaves. This example show various ways of making leaves by only tracing a printed stencil and by filling a contour with a different color. A printed object can be used as-is (Figure 10a–c). Three printing processes were used with the same printing path, and the printing times were 4 s (without preparation time for the paper), 24 s, and 2 min 48 s. A stem is drawn to combine the leaves, and these

[4]https://www.repetier.com/

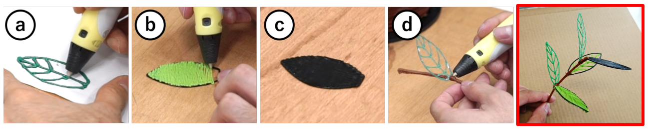


Figure 10: Example workflow using three different types of printing styles of the system.

are adhered using extruded material (Figure 10d). The whole work takes approximately 20 min.

Rabbit. First, by printing a stencil and contour lines, a sphere representing a body outline (Figure 11a) is created. The printed contour lines contribute to obtain a relatively accurate global shape, and the stencil is used for doodling multiple wireframes, creating small grids to guide hand work. Next, using the body outline, a body and head part are doodled (Figure 11b). By stroking the body with the extruding material at tip of the 3D pen, fluffy animal hairs are expressed. Finally, a tail, legs, and ears are added. Here, let us suppose that users want to create ears and legs that are sufficiently large to support the whole body with a flat bottom (Figure 11c). By using the system with the filling option, these parts can be created by the 3D printer. Filling takes longer (in this case, 5 min), but users can doodle a tail while printing other parts. All parts are integrated into the body, and the whole work takes approximately 30 min. Figure 11 shows the turn-taking between a human and the machine during the creative process. As a user utilizes a 3D printer during the process and not as a final output appliance, they gradually design the product collaboratively with the machine.

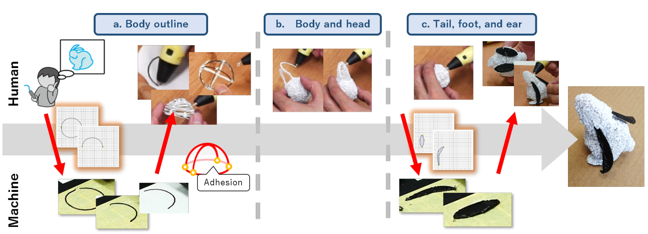


Figure 11: Example workflow using a 3D pen and 3D printer together.

6 USER STUDY

In this section, we introduce a user study with eight participants. The objectives are to understand creative activities with pen + printer; how a 3D pen, a 3D printer, and craft tools are used in the process with the proposed techniques and workflows; and how a 3D printer affects humans' creativity. We designed the user study referring to [4, 14, 39].

Participants

We recruited eight undergraduate/graduate students (P1–P8) from the university (No. female students = 3, age mean = 21.6, SD = 1.3). All participants were randomly recruited regardless of their prior experience with 3D printing and 3D pen use. Most of them had no or little experience, and a few participants (P1, P4, and P8) had experience with 3D modeling and 3D printing. We informed the participants of the purpose and overview of the study, the expected length of the study, the goal of the task (creating a 3D object designed by him/herself), and that data will be collected. The study was voluntary; participants could terminate or take a break if necessary. We paid the participants approximately $100 to compensate for their participation, regardless of the quality of their work or actual working time.

Apparatus

We set up the user study in a laboratory at the university. We provided two types of 3D pens to give more options with size and grip: 7TECH 3D printing pen and CRITIRON Intelligent doodler pen. Unlike 3Doodler[5], these pens have feed filaments with a diameter of 1.75 mm; this is the most common thickness for commercial filaments. Thus, we can provide a wide variety of materials as requested. The 3D printer used during the study is a consumer-grade FDM with a 0.8-mm-diameter nozzle for increasing the speed. We also provided a laptop to use our system, example images, videos of 3D doodling, and printed instructions. In addition to the 3D pen and 3D printer, participants could also freely use craft tools and materials, such as a tweezer, paper, a ruler, and clippers upon request. Participants' work and utterances were recorded by using a camera placed in front of them.

Procedure

Considering the contents and participants' fatigue, we designed two-day sessions consisting of practice and planning (Day 1) and making (Day 2).

Practice (Day 1). After a demographic survey, a participant learned how to use a 3D pen, tools, and a 3D printer in approximately 100 min. We provided printed instructions that included contents, referring to the bootcamp section of the 3Doodler book [1]. Participants might encounter challenges during the study, as newcomers may not be familiar with the given tools and setting, creating 3D objects using a pen and printer together, and utilizing craft materials and tools within a limited time. As indicated in [17], casual users often lose their engagement owing to tedious troubleshooting and struggling with non-creative tasks. Therefore, one of the authors played a facilitator role and provided help when it is related to techniques for handling tools.

Basic operation (15 min): We first showed how-to videos and explained the usage of a 3D pen, its mechanism, the differences between PLA and ABS, and the cautionary measures

[5] http://the3doodler.com/

for using the devices (e.g., the temperature of the nozzle and the odor of the molten material). Participants practiced three basic doodling techniques: following 2D shape primitives basic 3D doodling (pulling material), and filling a 2D plate while texturing controlling the tips of threads.
2D stencils (20 min): The participants created simple 3D shapes (a sphere, box, and cylinder) using stencils, a common doodling practice.
Craft materials and design mat (15 min): We provided craft materials such as crumpled paper, a glass bottle, a can, and a wooden stick; these can be used as a scaffold for 3D doodling. The participants practiced using a design mat[6], a heatproof mat that helps users to draw fine lines.
3D printer and the system (15 min): We explained the 3D printing process and our system and let the participant try to use it. The participant then doodled using a printed cylinder and box and printed contour lines using the system.

Planning (Day 1). After the practice session, participants were instructed to plan on what to make for the next session. The facilitator first let them provide any ideas but did not force them to use a specific tool including a 3D printer and our system. The participants discussed the feasibility of their plans with the facilitator, seeing examples of 3D doodled art works (e.g., Figure 3), and searched for 3D models on Thingiverse. If they were confused and wanted to know how to use our system, we gave instructions to make use of the design techniques. The participants wrote down a work plan for what to create on the next day of making (Day 2), the tools and material needed, and a reference image.

Making (Day 2). Participants started the making session by reviewing the usage of a 3D pen and their work plan. We allowed them to change their plan before and during the making session. According to the plan, we prepared materials and tools. Since several participants required a 3D model, the facilitator let them search on Thingiverse and use TinkerCAD[7] for 3D modeling. While observing the process, we sometimes asked questions to promote think-aloud protocols. They could terminate the session if they thought the work was completed. After making, the participants answered a questionnaire and freely talked with the facilitator about the work. The length of the making session depended on the participants (see the "Time" column in Table1).

Questionnaires

We created two questionnaires to evaluate the user study. A demographic survey (S1) was used at the beginning. In addition to the basic information, we asked participants to self-evaluate their expertise in traditional arts and crafting, and their prior experiences in 3D printing, doodling, and modeling. The wrap-up survey (S2) was to reflect on the making session. S2 consisted of questions related general impressions, challenges, preferences, etc. using various factors. We refer to the Creative support Index [11] and Shneiderman's principles for creativity support tools [34]. Participants rated their experiences using a five-level Likert scale and openly described them in written reflections.

Analysis

We collected quantitative and qualitative data including participant backgrounds (S1), the scores of collected from the survey (S2), and material and machine usage data. To observe the natural behaviors of participants, we conducted a discourse analysis by transcribing recorded videos. To understand the characteristics of participants' comments, we coded them in two dimensions: topics (a 3D pen, a 3D printer, or craft tools) and the intent of a comment (opinion, requirements, or question). We also analyzed the relationship between participants' work and the design techniques.

Results

Table 1 lists the selective feedback of S2, and Table 2 summarizes the analysis of the making session. All participants were able to complete their work. The working time ranged from approximately 30 min to 2 h depending on the participant. The 3D printer was used by almost all participants except P8. P1, P2, and P4 used it with our system; P1 and P4 used Contour, and P2 used Fill. P3, P5, P6, and P7 used it to print a 3D model. P8 only used the 3D pen and craft tools; therefore, P8 did not answer the question on 3D printer use (A9 and A10 in Table 1).

The average scores were high in general for many of the factors such as achievement, engagement, and enjoyment. The participants liked to play with the 3D pen (A8) and tended to like their own work (A1). Very high scores include 5.0 ±0.0 for engagement (A3). Although the working time was quite long, the participants answered that they did not feel that it was long (A4). As for the reason for this score, P3 answered "*because I can create intuitively*," and P6 answered "*because it seems to have various elements of craft*." The score for exploration (A6) also implies these comments. On the other hand, no participant evaluated the perfection of their work as 100% (Q2 in Table 2). The score on whether their work is replicable by others was neutral (A5). The participants felt that the 3D printer improves the efficiency of their work (A9) and makes them more creative and successful (A10). They identified the part that they were in charge of (Q1 in Table 2). On the 3D printing, P1 answered "*the 3D printer can reproduce 3D data that I created with high fidelity*," and P7 answered "*the 3D printer made it easy to fill things, which is tough work by hand*."

[6] https://www.the3dmate.com/
[7] https://www.tinkercad.com/

Findings

Difficulties with 3D Pen Use and Skill Development. The most notable comments from the participants during the practice session were regarding the difficulty of controlling the 3D pen. The difficulties are categorized into four types: stroke speed/direction, filling, bonding, and stringing. The Stroke speed affects the shape of the extruded material. P1 struggled with doodling uniform lines, while P4 and P8 compared this characteristic to calligraphy. P1, P6, and P7 noticed that the stroke direction affects the outcome because of the heat of the tip; especially, P6 compared this to a woody texture engraved with a chisel. P2 and P3 wrote that a doodled part became bumpy and bloated. Filling was tedious work because the participants had to keep doodling under the same conditions. P1 disliked this work and said "*it is not human work...*," and P2 associated this with for a statement in a computer program. P8 said "*I feel that I have become a 3D printer.*" Bonding is required to assemble a 3D shape from parts. P2 was confused by gathering material at a single place (e.g., at the corner of a box). P5 compromised with this and said "*an adhered part does not become clean anyway; it is no problem for me.*" Stringing is a well-known problem in 3D printing, and it also occurs with a 3D pen. During the practice and making sessions, the participants often struggled to remove a string from the extruded part and the tip of a 3D pen.

Table 1: Selected statements with survey scores. Scores are reported as *average* ± *standard deviations.* Since P8 did not use a printer, A9 and A10 are from seven participants.

* 1: Strongly disagree – 5: Strongly agree

Statement	1	2	3	4	5	Scores
A1: I like the work that I created. (Achievement)	0	1	2	1	4	4.0 ± 1.2
A2: I was able to express what I wanted to create. (Expressiveness)	0	1	1	3	3	4.0 ± 1.1
A3: I was very engaged in the activity. (Engagement)	0	0	0	0	8	5.0 ± 0.0
A4: I feel the working time was long. (Flow)	5	2	1	0	0	1.5 ± 0.8
A5: I think that it would be hard for others to replicate my work. (Ownership)	0	2	4	2	0	3.0 ± 0.8
A6: The 3D pen allows me to embody my idea quickly. (Exploration)	0	1	2	1	4	4.0 ± 1.2
A7: When planning, I was able to imagine how I would use the 3D pen (Expectation)	0	1	2	2	3	3.8 ± 1.0
A8: I like the 3D pen. / I like to play with the 3D pen. (Enjoyment)	0	1	0	3	4	4.3 ± 1.0
A9: The 3D printer improved the efficiency of the activity. (Collaboration)	0	0	0	3	4	4.6 ± 0.5
A10: I was more creative and successful when I used both pen and printer together. (Collaboration)	0	0	1	3	3	4.3 ± 0.8

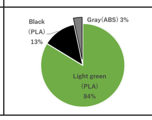
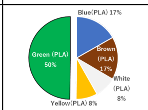
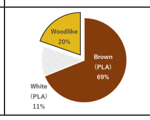
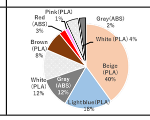
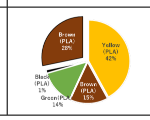
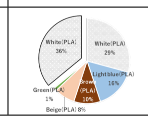
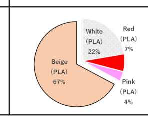
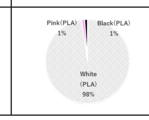
Although the participants faced various issues, they were becoming used to controlling a 3D pen step-by-step. Facing the above challenges contributes to learning how to use a 3D pen. In the making session, the participants attempted a variety of techniques that they had experienced. P1 controlled the tip of the 3D pen to express the texture of a seat of a chair. P4 utilized textures presented with the design mat to create a waffle cone. By bonding wires, P6 created ice cream, and P7 created a strawberry. P8 created a dog using only a 3D pen and developed a skill in his/her own way; P8 doodled a part in the unit of a facet and not a wireframe and mentioned "*I prefer assembling facets...it is similar to 3D modeling.*"

Use of 3D Printing with 3D Doodling. To overcome challenges, participants used a 3D printer in their work. We identified two times at which a 3D printer was used: at the beginning or middle of work. The participants except P8 started the making session with 3D printing. Printed objects tend to be large and simple shapes that may take a long time to doodle with manual work. For example, P2 printed the lawn for the stadium and used it as a base for other parts. P7 printed a sponge cake that was a cylinder with a diameter of 60 mm, and it took 47 min to print. These uses are inspired from technique 1; the 3D printer contributes to making it easy for a user to reach a predefined goal.

P1 and P4 also used the 3D printer at the middle of making. Using our system, P1 drew the frames of the chair, and P4 drew a ring and pillar for making the stand. Although these parts are quite simple and take several tens of seconds, they are important. P1's frames supported the entire shape of the chair and needed to be of the same shape. P4's ring supported and fit the cone as a part of the stand because P4 was not able to create an ideal size of the ring with the design mat. These are functional objects by combining 3D doodling with 3D printing (technique 7). As shown in the example workflows, our system allowed the participants to print while doodling. On the other hand, the "stencil" printing style of the system was not used. Instead of a stencil, P2 drew figures on cardboard with a ruler and marker pen.

While 3D printing, the participants were tightly engaged in 3D doodling. P6 doodled the foot of the bowl and answered "*it was good to work with the 3D printer while making it print a kind of large or fixed-size object.*" P7 spared time to doodle decorations (elaborate flowers and strawberries were P7's work). Therefore, the tendency of their strategy was to leave a large or global concept to a 3D printer to reduce the load of non-creative work.

Table 2: Results of the user study. "Material" indicates the amount of material used by each participant (bordered areas mean for 3D printing). "Printer" indicates the things printed in the study and the printing time (boldface means printing with the system). "Q1–Q3" are the questions selected from S2.

No.	P1	P2	P3	P4	P5	P6	P7	P8
Skill	3D modeling			3D printing		Drawing	Drawing	3D modeling
Work	 chair	 stadium	 bamboo shoot	 ice cream	 sun flower	 parfait	 cake	 dog
Time	30 min	65 min	90 min	2 hours	90 min	95 min	2 hours	2 hours
Material								
Printer	**frames** (0:18) *3 times	**lawn** (9:09)	lower part (6:46)	berry (3:18) **ring** (0:23) **pillar**(0:27)	seed (8:43)	bowl (14:35)	sponge cake (47:13)	–
Q1	80%	80%	60%	75%	90%	80%	60%	100%
Q2	70%	60%	50%	90%	70%	85%	90%	80%
Q3	clipper	design mat	bottle	design mat	spatula, ruler	tweezers	clipper	tweezers

Q1: Indicate the proportion of the part that you did. Q2: What is the degree of perfection degree of your work?
Q3: Except for the 3D pen and 3D printer, which tool did you use the most?

After printing, several participants customized a printed object using a 3D pen and various materials (the materials used are shown in Table 2). P2 doodled white lines on the lawn, P5 added bumpy textures to a cylinder to express the center of a sunflower, and P6 doodled patterns around an ice cream bowl as decorations. Obviously, the various types and properties of the materials used in this study (technique 4), especially color, are used in their work for aesthetics. Texture expressions using a 3D pen are inspired by technique 3.

Deciding What to Create Hands-on Versus What to 3D Print. We found that some participants' work could be improved if they used the 3D printer. P2 marked the degree of perfection of his work as 60% because the ground and white lines became unsatisfactory with his hand doodling. As it is difficult to draw a straight line with a 3D pen, those parts should have been printed. P3 noted that "*because the top of the bamboo shoot that was made was with short...I feel that I have failed.*" However, it took only 6 min to print, and P3 could have scaled up and printed a part again. P5 spent most of the time doodling approximately 30 petals. P5 further said "*I wanted to bend a petal at the center,*" but it is very difficult to glue all petals. P8 did not use the 3D printer at all, but he muttered the need to use 3D printing when filling the surface after making the outline. In contrast to using technique 2, P8 tried to obtain a global concept by him/herself.

Use of Craft Tools. Various craft tools were used by the participants (Q3 in Table 2). These were mainly for technical skills such as picking up a part and removing unwanted threads and oozed materials. Akin to the natural practices in crafting, the tools were used to trim, adjust, and rework their objects. While making, P1 always held a clipper and tweezers to trim the object. P7 picked up a part using tweezers to prevent it from touching the pen tip; furthermore, P7 used the tweezers as a scaffold to support the structure of a strawberry. P3 used a glass bottle to reshape the doodled skin of the bamboo shoot. P3 noticed that PLA can adhere to the surface of a glass bottle, and the bottle generates a glossy surface. P2 used the design mat to create poles that have the same size and a flag-like shape. P4 realized that the mat can express a waffle texture and therefore doodled a large sheet to later deform it into a cone. We found that the creative use of craft tools also empowers the participants' creativity. If a 3D printer contributes to the creation of on-demand tools, the activity can be further improved, as shown in technique 5.

Several participants used the 3D printer as one of the craft tools. To create the frame of a chair, P1 printed the same part three times, mentioning "*the third is a spare, just in case.*" P4 used the printing bed as a heater to roll up a waffle cone. Since the participant had experience with 3D printing, P4 understood the nature of the material and machine; PLA can become soft by touching the heated bed. P6 explored a support structure generated inside a bowl printed upside-down. P6 first tried to get rid of the support using a clipper. Later, P6 noticed that the support can be used as a pedestal to settle the ice cream and thus did not try to completely remove it.

7 DISCUSSION

Efficiency Versus Creativity

In our study, participants faced four types of challenges. Tedious iterations of simple and boring tasks, e.g., filling a large surface, assembling and welding parts, and flattening a surface, particularly made participants lose interest and think that the process is inefficient. Participants were able to improve efficiency by delegating such tasks to the 3D printer, focusing more on creative tasks.

On the other hand, fear of failure seemed to increase while using a 3D printer and can hinder the exploration of creative tasks. As a 3D printer can finish parts with accurate shapes, users tried to take advantage of this benefit. We found that users tended to regard a 3D printed part as one of the completed parts and seemed to be resistant to doodling on it. However, P4's waffle cone that was post-deformed and P6's support structure printed in the bowl are serendipitous inventions during craft process. This implies that using a 3D printer as a tool and manipulating partial outcomes are important factors that induce user's creativity.

As summarized in Table 1 (A5), the answer regarding the replicability of their work was neutral. This is a trade-off between the efficiency of the process and the expressed creativity. Thanks to 3D printing, 3D modeling, and online communities where users share free designs, everyone can replicate objects by only downloading and modifying them. However, the more a participant pursues fidelity and efficiency, the less the ownership of his/her work is, as they do not believe that the work is creative and feel ownership of the product. Wrapping up the study, one participant who was good at 3D modeling stated that he can also create the same 3D data with screen-based 3D modeling software.

Roles of Humans and Machines in Creative Making

A 3D pen enabled our participants to quickly validate and explore their ideas, allowing direct manipulation of the tool to externalize a conceptual idea. Aiming at inventing a new process in which humans can focus on creative tasks, the important roles of the 3D printer are to ensure that users approach a goal step-by-step and to make users freely explore ideas. We observed that the participants printed large parts (P2's lawn, P5's seed, and P7's sponge cake) while doodling small details, and functional parts (P1's frames and P4's stand) were well-produced with a 3D printer.

When 3D printing, the size, material, color, and shape of the object should be determined at the design stage and not the physical fabrication stage. This informs us that 3D printing by a machine affects what is doodled by hand and how large this doodle is. In our study, most participants started the session with 3D printing; especially P2, P5, P6, and P7 were thinking about the relationship between the sizes of the objects being printed and doodled. This process should be mediated to promote exploration with a 3D pen, e.g., by printing various alternatives. On the other hand, by experiencing this stage, users acquire an important key to creation; users need to consider the size and arrangement of the final outcome. This means that a 3D printer provides constraints to exploration, and hopefully, users progress to the next step with this constraint. One of the steps is aesthetic customization using a 3D pen, which a user can easily improvise with their fine hand skills. For example, it is difficult to make a multicolored object with conventional 3D printing alone (e.g., chocolate drizzle around ice cream) owing to the limited color palettes available. By obtaining a printed object, humans can use it as a canvas for personal expression.

A major difference between a 3D pen and a 3D printer is that creation with a 3D pen does not require any concrete idea of creating the object before a user actually "starts" the creation. Users can start by creating some primitives. It does not involve batch processing to complete the final outcome. While directly manipulating a 3D pen, users can learn various factors, e.g., the height of the nozzle creates a unique texture [35], the stroke speed is related to the extrusion, and some errors (e.g., stringing and layer shifting). It resembles a traditional craft experience in that users gradually learn how materials and tools behave while making and hence can adapt a strategy to deal with the techniques and 3D printer.

Limitations and Future Work

Our study aimed to observe creative tasks within a limited time frame, in a limited space. The participants often considered the trade-off between the working time and what they wished to make; they had to reduce the overall size of the object and disregard some details. It is viable that participants can use the 3D printer in a limited manner to divide tasks for the 3D printer to compensate for time limitation. Our next goal is to not limit the time and space, so that participants can explore greater varieties of constraints and possibilities. We possibly may find a new significant role of the 3D printer as an intelligent agent that can aid a human's creative process.

8 CONCLUSIONS

In this work, we explored the opportunity and capability of *3D pen + 3D printer* in creative making. On the basis of a pilot study, we identified possible challenges and introduced seven design techniques to innovate the 3D modeling process with example workflows. We also conducted a user study to observe the behaviors and roles of humans and machines in creative activities. We found that the participants were highly engaged in making and felt that these new workflows helped them be creative. We discussed the roles of humans and fabrication machines and the future of fabrication.

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