# 3D Sketching and Flexible Input for Surface Design: A Case Study

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***Abstract*— Designing three-dimensional (3D) surfaces is difficult in both the physical world and in 3D modeling software, requiring background knowledge and skill. The goal of this work is to make 3D surface design easier and more accessible through natural and tangible 3D interaction, taking advantage of users' proprioceptive senses to help them understand 3D position, orientation, size, and shape. We hypothesize that flexible input based on fabric may be suitable for 3D surface design, because it can be molded and folded into a desired shape, and because it can be used as a dynamic flexible brush for 3D sketching. Fabric3D, an interactive surface design system based on 3D sketching with flexible input, explored this hypothesis. Through a longitudinal five-part study in which three domain experts used Fabric3D, we gained insight into the use of flexible input and 3D sketching for surface design in various domains.**

***Keywords—3D interaction; 3D sketching; fabric; flexible input surface design; 3D modeling; garment design***

## I. Introduction

3D surface design, the process of envisioning and specifying the external surfaces of 3D objects (such as cars, furniture and garments), requires much background knowledge and skill in order to make a desired surface. For designing surfaces in the real world, such as when making garments, the designer needs to know how to drape fabric, fit to the human body, and use a sewing machine, among other things. Cutting mistakes, such as sewing the sleeves to be too tight or too short, cannot be easily fixed or undone in the real world. For designing surfaces in the virtual world, 3D modelers need to master a wide array of features in 3D modeling programs that manipulate a series of connected polygons, most based on 2D mouse interaction. To help lower the learning curve for making these kinds of objects, we have been exploring more natural 3D interaction for surface design.

One idea for more natural 3D surface design is to use 3D sketching. We hypothesized that directly drawing a surface in 3D space would be easier to learn and use than existing surface design tools. In our exploratory study of how users intuitively communicated different 3D surfaces [1], we repeatedly observed 3D sketching actions. 3D sketching is an interaction used in virtual art applications as well [2, 3].

In order to handle the variety of shapes a user could want and give the ability to draw more than one point at a time, flexible input based on fabric can be used. Fabric can be bent and folded into different shapes representing part of a 3D surface, and it gives the user a tangible representation of the surface. A user's proprioception, or understanding of a muscle's location based on other muscles [4] may make it easier to transfer envisioned ideas into the virtual world through this tangible medium.

The combination of 3D sketching and flexible input for surface design led to the design of the Fabric3D system [1], which allows fabric to act as a malleable brush that can be used to paint surfaces in 3D space. The goal of this work was to explore and evaluate Fabric3D for surface design applications.

In the evaluation reported in this paper, our main goals were to explore how flexible input can be incorporated in various domains of surface design, to discover how surface design domain experts use a flexible input & 3D sketching system to design surfaces, and to understand how that design process changes over time.

Neither flexible input nor 3D sketching are traditional interactions for surface design software, so we anticipated that domain experts would need to explore such a system as they got used to it. In a longitudinal study, we found that users explored by brainstorming, playing around with ideas, and evolving them into a full sketch. This evolving, playful interaction style had significant implications for how participants used the system, what they made, their attitudes towards flexible input and 3D sketching, and how they felt it applied to their work. We found several themes, including trade-offs between 2D and 3D sketches, playfulness, and different design challenges in flexible input.

## II. Related Work

Below we discuss 3D interaction for modeling, 3D sketching, and flexible input. While at first glance our work may appear similar to virtual fabric simulations, such as the garment design systems described in [5], these systems are all based on keyboard and mouse interaction, can only manipulate one point or line at a time, and use virtual fabric. Our work focuses on the use of physical fabric as an input device for 3D surface design.

### *A. 3D Modeling in 3D UIs*

Various 3D modeling systems that use 3D interaction have been influential in how we approached the design of our system. Sasaki et al.'s Facetons system used an HMD and a tracked object to place rectangle primitives in the world to make architectural designs [6]. THRED [7], Shaw's free form polygonal surface design system, enabled users to sketch freeform surfaces with a three-button sensor held in each hand. Tasks such as picking and manipulation were accomplished with the user's dominant hand, while the non-dominant hand handled context setting and system commands. The two-handed approach for sketching surfaces freeform is an idea also supported by our design of flexible input.

Lapides's 3D Tractus [8] was a freeform 3D drawing board used to sketch models and surfaces using a TabletPC and a height-adjustable stand. Users drew with the Tractus by using a TabletPC and varying the tablet's height simultaneously. This pen-based interaction is an improvement over a 2D sketch interface because a 3D line or area can be created with a single interaction. Our system removes the requirement that the drawing has to take place on a surface, and allows sketching directly in 3D space.

### B. *3D Sketching in 3D UIs*

3D sketching in the air is a popular and viable interaction for 3D UIs, particularly for artistic applications. The CAVE painting project [2] supported 3D interaction for painting in the air using a brush, pinch gloves, and a table. Schkolne's Surface Drawing [3] enabled users to generate 3D lines and shapes through repeated markings and brush strokes in the air. The work featured an AR system with tools to generate lines based on hand and fingertip movements, and targeting art students. Yee et al. presented a 3D AR sketching system that used real-world objects as references [9]. Lau et al.'s Situated Modeling system used real-world objects to "stamp" virtual objects, giving a tangible guide for their virtual objects [10]. Our work extends these approaches by evaluating tangible, flexible fabric as an input device.

### C. *Flexible Input*

Flexible input devices have been made from a variety of materials for a variety of different applications. Lee et al. [11] conducted an exploratory study on how paper, elastic cloth, and plastic could be used to represent various system and 2D commands such as zooming in and closing a window. Their work complements our work in 3D interaction, except in a specific application.

Sponges as flexible input to manipulate a virtual object were explored through Sheng et al.'s work [12]. Users interacted with the sponge through finger presses, gestures and visual widgets. Informal feedback showed that such interfaces were easy to learn and expressive, yet may fatigue the user.

One of the most closely related systems to our own was Balakrishnan et al.'s use of ShapeTape, a tracked flexible tube that enabled two-handed and direct manipulation [13]. The curve device was mapped to a virtual reference curve in the virtual world. A surface was created by first positioning the ShapeTape and taking a snapshot of it. The reference curve was manipulated using the ShapeTape, using actions such as rotating and twisting. Our work builds on these concepts by exploring a 2D flexible surface, and keeping two-handed interactions to support rotations, twisting, and other manipulations. In an evaluation of ShapeTape, Baillot [14] found that users were able to write text using one end of the device, but experienced many pointing errors. We had similar concerns about lack of precision with our flexible input.

We started exploring the design space of flexible input and surface design by conducting an exploratory study observing how users would communicate different shapes. We extracted interaction themes, and from those themes, designed and evaluated the preliminary version of Fabric3D [1], and after the results of the preliminary study, this paper discusses an in-depth study on such a system, its flexible input interactions on surface design.

## III. System Design

Fabric3D is an experimental surface design system that helped us explore how 3D sketching and flexible input can be combined. After our preliminary evaluation, we saw both promise and improvements on the system. We outline the system briefly, along with the improvements below. For more design details beyond this brief overview along with the results from the preliminary study, please refer to our earlier paper [1].

### A. *Flexible Input and Sketching*

Fabric3D's most important features are its tracked flexible input and 3D sketching using flexible input.

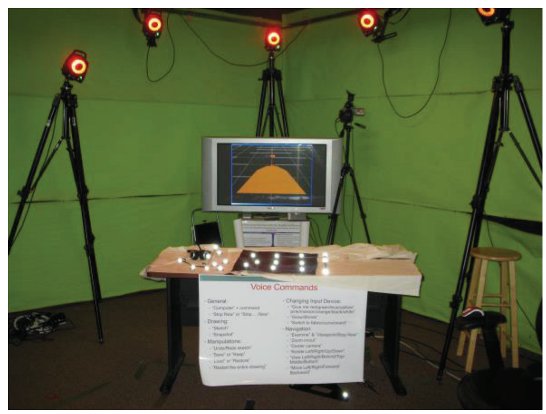


Fig. 1. Physical setup of the Fabric3D system, with most cameras focused on the user. The user held an input device with tracked markers.

For tracking the user's head and the flexible input devices, we use a VICON vision-based tracking system that tracks retro-reflective markers. Tracking works best when at least three cameras can see a marker and all the markers are visible. Some manipulations of the fabric, such as folding, result in poor or lost tracking.

As shown in figure 1, we positioned the cameras to be close to the display, focused on the user workspace. We instructed users to keep the markers visible to most cameras for better tracking.

Flexible input is used as a dynamic moldable brush to sketch in the air. Fabric3D has three sketching input devices and two supporting input devices, as shown in figure 2.

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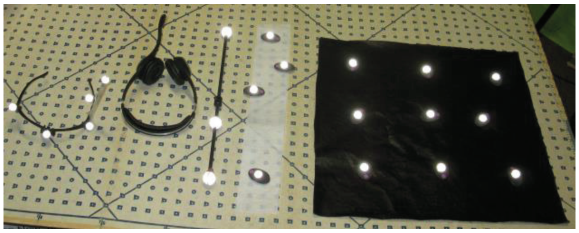

Fig. 2. Input devices from Fabric3D, in order from left to right: glasses, headset, wand, fabric strip, and fabric square.

- **Wand**: The wand (non-flexible input) is a VICON calibration wand that can be used to draw single dots or, in sketch mode, a series of connected lines. The wand has the best tracking simply because it is rigid.
- **Fabric strip**: This is a flexible strip made out of interfacing material, a thick type of fabric. This device can be used to draw thin curves mapped to the bends and twists of the strip, similar to ShapeTape [13]. The virtual curve uses the four tracked markers as the control points for a Bézier curve.
- **Fabric square**: This is a 12in x 12in fabric square, with a grid of tracking markers attached. The fabric is made from plastic leather, a decision made based on the exploration of materials in our past study [1]. The fabric square can be used to draw a virtual surface patch with the bends and twists of the physical fabric square. The virtual surface is a triangulated mesh of the nine tracking markers.

We were aware that it would be difficult for the tracking system to track the fabric square or strip if the user bent or folded it, since the markers could easily get occluded. Nonetheless, we felt the system was functional and usable enough that we could still learn something about how people use flexible input and 3D sketching. There are two ways to draw with these input devices:

- **Snapshot mode**: Our input devices generate a virtual surface patch, curve, or point. Snapshot mode is used to draw only a single copy of this output, as though the system is taking a picture of the input device.
- **Sketching mode**: Sketching mode is used to draw continuously, like a paintbrush or pencil. In our implementation, this mode draws a dense series of copies of the output generated by the current input device.

### *B. System Controls*

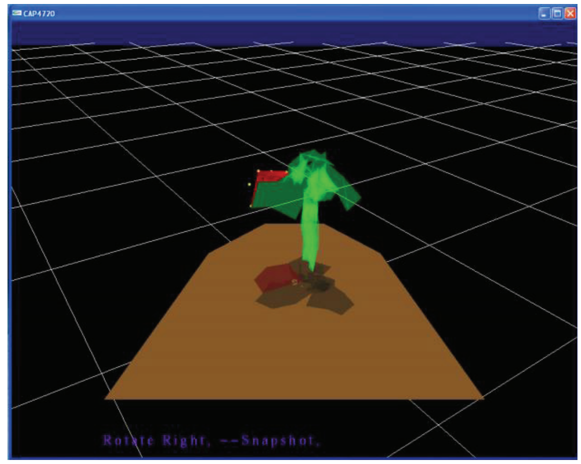


Fig. 3. Screenshot of Fabric3D system. The red region is the current input device location while the green areas have already been sketched. The tracked user workspace is shown in brown on the ground plane.

To use Fabric3D, users stand in the tracked workspace, wear the headset and tracked glasses shown in Figure 2, and pick up the wand, strip or square to use for drawing. After picking an input device, the user informs Fabric3D which input device is active through voice commands.

The user is tracked within a roughly 2.7 x 2.7 meter area. As shown in Figure 1, we placed a table in front of the tracked workspace as a place to both set down the input devices and to show a printed list of voice commands. Visual output is shown on a TV, and audio output plays through the headset.

Figure 3 is a screenshot of the user interface. It shows a virtual world with a ground plane, a brown area on this plane representing the tracked workspace, the virtual representation of the current input device (red), and the current drawing (green).

In our previous study [1], we found that fabric tends to afford two-handed interactions, so we wanted Fabric3D to use hands-free commands. Thus, system control is performed via voice commands through a wireless microphone. Users can issue commands such as starting or ending a sketch, taking a snapshot, undoing or redoing the last sketch, changing colors, changing the size of the virtual input device, saving/restoring the sketch, and navigating through the virtual space.

We also designed a navigation mode called examine mode, using head tracking provided by the glasses shown in Figure 2. Users can employ examine mode to orbit around objects as they draw them, which was a commonly-requested feature during our previous study [1]. The user can move around a sketch by moving the head relative to the active input device, providing an effect similar to fish tank VR [15], except that the virtual camera always points towards the center of the current drawing.

## IV. Experiment

### A. Research Questions

Our major research questions were:

*1. How relevant and useful is flexible input and 3D sketching for the various domains that the participants are domain experts in?*

We wanted to understand the usefulness and applicability of flexible input and 3D sketching for various application domains. We were interested in how sketches in Fabric3D differed from surfaces designed with other tools, how the surface design process differed, and how easy it was to transfer ideas to the system using flexible input and 3D sketching.

*2. How do the sketches and the creation process change as participants use the system?*

We knew that Fabric3D would be a new experience for users, so we expected both what they drew and their creative process to change as they got used to the system. We wanted to see how our experts handled the tracking issues and how that would change what they made. The previous study had one participant take advantage of the tracking issues; he made clouds by crumpling up the fabric into a ball [1]. We were interested in this evolution of product and process, and how participants felt about the system after spending significant time with it.

### B. Participants

We targeted domain experts in various fields incorporating surface design to be participants in this study. Domain experts understand in detail the kinds of tools, processes, and creations common in their domain of expertise. Experts were also novices in the past, so we see their experience valuable as an expert, a former novice, and their journey to becoming experts. We also want to see how their creative process changes with our longitudinal study from using familiar tools to an unfamiliar tool like our flexible input. We defined an expert as someone having three or more years of experience in the field. We had a garment designer, an architecture grad student, and a 3D modeler as participants, with ages ranging from 20 to 57.

**Garment designer**. She brought 40+ years of experience in constructing garments, home décor, and design. She also had some experience in design software for drafting garment patterns, and drafts clothing patterns by using existing patterns and changing the shape to better fit a client's measurements.

**Architecture Ph.D. student**. She used a wide variety of 3D modeling software to make objects and surfaces, ranging from 3D modeling software like AutoCAD and Google Sketchup to lighting design software.

**3D modeler**. He had six years of 3D modeling experience on programs such as AutoCAD and ZBrush. He also had some experience in costuming and using design hardware such as a Wacom tablet for 3D modeling.

### C. Experimental Task

We gave participants the task of sketching an idea of moderate complexity with respect to the participant's discipline. We did not want participants to sketch out the simplest or most complex ideas because we did not want them to believe it was too easy or too hard to sketch with flexible input. Participants performed the experimental task five times, with a few days separation between tasks. While doing the experimental task, participants could ask for help from the moderator. If the moderator observed that the participant was having too much trouble with something, the moderator would suggest hints or help.

### D. Experimental Procedure

In order to get answers to questions relevant to process and how sketches changed, we conducted a longitudinal study with the domain experts. The study lasted for six sessions, with the last session being a focus group. There were no time restrictions set for any portion of the experiment, since we did not want time to bias participants to draw simpler or more complex sketches.

A participant started the first session with a pre-study questionnaire to collect background data and domain-specific information. The participant was then introduced to Fabric3D, and the system was trained to recognize the participant's voice. We then had a Fabric3D practice session, after which we provided the participant with paper to brainstorm ideas to be sketched with the system. Next, during the experimental phase, the participant performed the experimental task. After finishing their session with Fabric3D, we asked participants to revisit their brainstorming sheets to add, revise, or remove ideas, and the session concluded with a post-questionnaire and an interview.

During sessions 2-4, we started with a simple warm-up exercise, during which participants drew a heart, tree, and pyramid, using each of the input devices once, assigned at random. We gave the participant the option to revisit already-sketched ideas, but we did not allow them to reload old sketches to encourage a new sketch for every session. After the experimental phase, we asked participants to revisit their brainstorming sheet. Once again, we concluded with a post-questionnaire and interview.

Session 5 was exactly the same as sessions 2-4, except that we had an additional post-questionnaire and an additional set of interview questions, both of which focused on overall usability and personal reflection. The final session of the study was a focus group discussion of participant experiences during the study.

### E. Data Collection & Metrics

Given that our research questions focused on a change in process and reflections, we collected a variety of qualitative data. The list below shows the different ways we collected data and the metrics used for each method:

**Pre-questionnaires** were used to collect background data, demographics, experience, and data about the creative process in the participant's domain of expertise including the tools used.

**Moderator-recorded observations** were collected through notes taken during the session. The experimental sessions were recorded and later viewed to see usage trends of Fabric3D between the different devices, and to identify usability issues. We also recorded every voice command to detect significant voice misrecognition issues or frequently used commands.

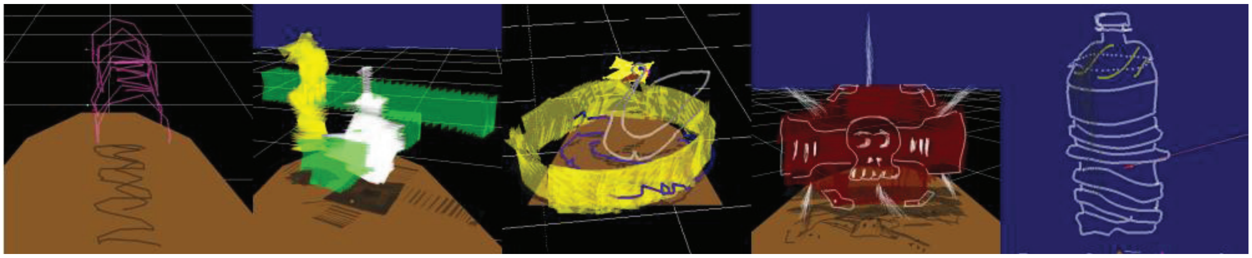

Figure 4(a-e). Various sketches drawn by participants from left to right. (a) An arbor was the last sketch made by the garment designer. (b) The architecture student sketched buildings on her 4th trial, and (c) a swan in a lake on her last trial. (d) The 3D modeler sketched a pauldron (shoulder armor) on his 3rd trial, and (e) a water bottle on his last.

**Participants' sketches** were categorized as organic, geometric, abstract, or non-representational. These classifications came from Lewis & Lewis's The Power of Art [16]. They defined geometric shapes as those made with straight or smoothly curving lines like circles, while organic shapes use jagged, uneven, or irregular curves. Abstract shapes are defined as simplified representations of real-world objects, potentially with some distortion. They may represent geometric or organic shapes. Non-representational shapes do not appear to represent anything found in the real world. We conducted the sketch analysis on whether the resulting sketch had components of any of these kinds of shapes, so it was possible for one sketch to contain all of the kinds of shapes.

Since the experiment focused on the participants and their expertise, we asked our participants to estimate how complex their sketches were relative to the objects made in their discipline. It was possible for a sketch in Fabric3D with few elements to be considered complex in a specific domain.

We also analyzed what input devices were used to make each sketch, along with how much time was dedicated to drawing the final sketch, in case the participant either drew many sketches that weren't final or failed to draw the final sketch the first time.

**Post-questionnaires** were used as a warm-up to the interview and to check on the participants' fatigue levels. The post-questionnaire focused on the sketching session that day, such as how complex the participants' intended sketches were, how those sketches related to the kinds of creations in their professions, and how satisfied they were with the sketches. We also provided an additional post-questionnaire in the final session, which asked the participant to compare the tools the participants used in their work to Fabric3D, to encourage the participant to think critically about how Fabric3D could be applied to their profession.

**Guided interviews** encouraged the participant to think about the what, why, and how of the sketches, and how they felt about the process and the result. We also had reflection questions about how Fabric3D supported their creative process, and whether they changed how they used the system compared to previous sessions.

**A special additional set of interview questions**, used after session 5, focused on reflection of their experiences with Fabric3D and how flexible input could be used in their profession.

**A focus group** was crucial in getting overall impressions, reflections and comparisons of different user experiences. The rest of the data were participant-specific, so the focus group helped us see overarching themes and helped the participants connect or contrast their experiences based on the experiences of other participants. Due to scheduling, we could not get the garment designer in the same focus group as the other two participants, so we asked the focus group questions to her separately.

## V. Results

We present the results with respect to each of the research questions.

### *A. Relevance and usefulness of flexible input and 3D sketching in various domains*

We found that participants saw Fabric3D as an imprecise conceptual or pre-conceptual tool to help brainstorm ideas.

#### *1) Sketches in Fabric3D versus other tools*

**There was a lack of connectedness while sketching.** Connectedness was defined as how different parts of a sketch might snap, align, or connect to other parts. Fabric3D had no connected joints or methods to connect two sketched elements together. Whether connection meant snapping points of different parts of a sketch together in software (noted by the architecture student and 3D modeler) or pinning pattern pieces together (garment designer), connection was important to all participants.

In the middle of the first trial, the 3D modeler tried to make a cube, with the walls of the cube connected together. After finishing the sketch, rotating the sketch, and finding the faces were not connected, he exclaimed how "amazing it is that you can't join it up." From the focus group, we found that the most "basic flaw [is] that it gets disconnected with the points. Small things interfere with the creative process." While precision issues with 3D sketching [14] and thus, the challenge of connecting edges in the air was expected, the unanticipated result was how important connection was in the participants' creative process.

**Fabric3D was better suited to sketches that were neither symmetric nor geometric**. Geometric shapes were reported to be extremely difficult. When the architecture student tried to sketch a pyramid during the practice sessions on days 2-5, she restarted a total of 18 times. When the 3D modeler sketched a tilted 2D helmet using the wand, he later explained during the interview that if he had done the helmet facing straight on, and if both sides of the helmet didn't look mirrored, the sketch would look poorer than drawing a helmet tilted down. The freeform nature of 3D sketching made it difficult to create precise geometry.

**Rough, unrefined sketches**. Visual examples of these rough, unrefined sketches are the jagged corners made by the square in figure 4b and 4c, where the yellow squares form an uneven jagged edge. The 3D modeler noted that rough, unrefined sketches look unprofessional and in poor form in his domain. The only sketches that ended up having a smooth edge were edges made by the wand in sketch mode, as shown on the edges of the water bottle in figure 4e. The smooth edges as a result of the wand were only a result of software, since sketch mode for the wand automatically connected each dot with a line. The jagged edges for the strip and square were a result of a lack of connection between the individual curves and surface patches created by those tools.

*2) Creative process in Fabric3D versus other tools*

**Unexpected sketching results.** Specifically, participants felt a lack of control with the flexible input, as expected from previous work [14]. This lack of control caused accidental or unintended sketches with Fabric3D. After the third trial, the garment designer discussed how she had trouble controlling the fabric square and strip. As expected, the wand had the highest level of control, as reported by all participants during the focus group.

With this lack of control, participants also noted unintended sketching occurrences. For example, when discussing the creative process after the first trial, the garment designer felt that while Fabric3D supported the creative process, the results felt accidental instead of pre-determined. At the end of his fifth session, the modeler felt that there was great difficulty in manipulating the fabric to a desired shape, since the "[fabric square is only] a square shaped polygon no matter how you use it, unless you fold it up but then it kind of bugs out." Overall, we observed that participants found it very difficult to mold the flexible input into a desired shape, and maintain that shape while sketching, while simultaneously keeping the tracking markers visible.

This sentiment of unpredictable results also came from an expectation that sketched pieces would be connected when they were not, as explained above. During the focus group, another related issue was feeling a lack of scale or proportion.

**Playing around.** The process of playing around was to create many different kinds of sketches to see what the result would be. This strategy of interacting with Fabric3D differed from that of simply focusing on a single idea to sketch and building upon that idea. The garment designer exhibited this behavior, since her final sketches ended up taking less than 10% of her total experiment time for three of the five sessions. She ended up making 25 distinct sketches with numerous restarts, despite reminders of the undo and redo features. At the end of her second, fourth, and fifth trials, the garment designer reported that she generally did not have a preconceived notion of what to sketch, despite the provided brainstorming time. During her first trial, the architecture student reported during the interview that she had to play around with Fabric3D since it did not give her much control.

Sometimes, playing around with the system led to building upon ideas. During the third trial, the architecture student noted that she had intended for two curves to meet at the center, but once she discovered that the curves were not in the correct positions, she incorporated the error into her sketch.

*3) Usage of flexible input and 3D sketching modes*

Overall the non-flexible input (wand) was the most preferred and most used input device among participants. The wand was involved in ten out of fifteen sketches, while the square was used in seven of fifteen and the strip only in five of fifteen. Five sketches were made entirely by the wand. Two of the three sketches drawn by participants in the final session were made using only the wand, as shown in figure 4a and 4e. The wand was the favorite input device as reported in the post-questionnaires, and was cited as the device with the most control and the device with the smoothest edges.

In terms of shape complexity, participants did not make complex curves or shapes with the flexible input. Flexible input was rarely bent, folded or molded into shapes. This result is at odds with what happened in the pilot study [1]. But given the existing tracking issues, the result was not surprising. The modeler noted in the second session that even tilting the square resulted in tracking issues. When the square was used in the final sketches, the square was either held vertically, as shown in figure 4b-d, or horizontally, like the buildings in figure 4b. The strip was mostly either straightened, like the white spike above the skull in figure 4d, or slightly curved like the white spike below the skull. There was only one instance where the strip was bent into an irregular curve, but this was during the third trial of the architecture student, who was finishing a sketch of a pathway.

Whether using flexible or non-flexible input, all but two sketches were made entirely out of continuous sketching. Besides the sketch in figure 4b, the only other sketch drawn with some use of the snapshot mode was a 2D pattern of squares, made by the architecture student, using the square held vertically upright.

*4) Usefulness of flexible input and 3D sketching*

**Conceptual tool.** Participants agreed that Fabric3D would be best as a pre-conceptual or conceptual tool for helping brainstorm or evolve ideas. During the focus group, the participants described Fabric3D as being closer to pencil and paper than to their traditional tools. The 3D modeler described how he used a Wacom tablet, but never touched it until he was absolutely certain of what he was creating, due to the high investment of modeling something using the fidelity provided by the tablet. In contrast, Fabric3D was seen as a fast way to sketch something. The architecture student described Fabric3D as primitive, but useful for basic and preliminary sketches. The 3D modeler described the kinds of low-fidelity ideas that were well suited in Fabric3D: "A tree is open to interpretation. I can have one sad branch like a Charlie Brown tree or a fully grown tree. So it's best for things where you don't have a pre-conceived notion of it."

**Limited use.** As mentioned in the focus group, one of the disadvantages was that the sketches were of low fidelity or quality, due to the rough results, lack of control and connectedness and unexpected results in sketches, as somewhat anticipated due to inherent tracking issues and 3D sketching disadvantages. The participants desired many other features that would make Fabric3D more usable, such as adding keyboard and mouse support, and the participants agreed that Fabric3D might also be better suited for viewing of 3D models rather than creating them. The garment designer felt that Fabric3D would be great for designing 2D fabric design patterns. This is supported by our observation that the most of the sketches were 2D sketches; there were fewer successful 3D sketches.

*5) Flexible input and 3D sketching to transfer ideas*

Due to the limitations of the system's usefulness, the unexpected sketching results, and the lack of connection between shapes and points, we conclude that Fabric3D was not an easy way to transfer ideas from the mind of the user to the digital world. One of the focus group participants noted, "You can imagine sculpting or something and raise one point. There are so many varieties. It was so flexible. But it's the basic flaw that it gets disconnected with the points when folded. Those small things interfere with the actual creative aspect."

### B. *Changes in sketches and process*

*1) Kinds of sketches*

In figure 4, we show some of the sketches that the participants made throughout the course of the study. The final sketches made in each session were mostly 2D, with ten out of fifteen sketches being in 2D. Four sketches were in 3D, including figure 4a, and the sketch in figure 4d was in 2.5D. In addition to having rough, unrefined sketches, users made shapes that were:

**Geometric**. Ten out of the fifteen sketches produced at the end of experimental sessions had geometric elements in them, whether the curved, yet rough-looking arbor (fig. 4a), the buildings (fig. 4b), the cylindrical boundary (fig. 4c), the rectangular shapes in the armor (fig. 4d) or the water bottle (fig. 4e).

**Abstract**. Nine out of fifteen total drawings had some simplified representation of shapes, whether it was the buildings in figure 4b, the swan in figure 4c, or the skull in figure 4d.

**Organic**. While few of the sketches in the experiment had organic shapes in them, our participants discussed how sketches like the tree in the practice session were ideal for Fabric3D. As one expert commented in the focus group, "[Fabric3d is] best for organic things that you didn't have a preconceived notion of it. If it doesn't look like a [pyramid] it doesn't look good. But a tree, or organic has zero symmetry, so it works really well and it looks better without symmetry."

We found no non-representational shapes in the set of sketches. We also found no connection between the kinds of shapes made, the levels of satisfaction and with time used in the experiment.

*2) Evolving creative process*

**Learning to use physical 3D space.** The garment designer changed her creative process as she explored how to use 3D space to sketch. Her first two sketches, an outline of her body and a fabric pattern, were both in 2D. But, during her third trial, she brought in a physical hula hoop. She brought it in to explore its movement by taping the fabric strip onto the hula hoop, and sketching while the hula hoop looped around her arm. After seeing the 3D lines that resulted from 3D movement, by the time she ended her third trial, she concluded during the interview that she needed "to draw around the space."

During the fourth trial she explored how to use depth by using the shadow of the wand to draw a picture, with the brown ground as the canvas, and the shadow as paint. In order to do this successfully, she had to walk around and back and forth to see the effects that moving around the space had on the shadows. While the sketch itself didn't represent anything, she wanted the 2D shadow to be her sketch. She used fully 3D movements to make her final sketch, the arbor in figure 4a, by oscillating the wand side-to-side and moving forward simultaneously.

The modeler learned to use depth differently than the garment designer. During the second trial in making the pauldron, shown in figure 4d, he learned to use depth to layer different parts of the pauldron. The pauldron started with the backmost square of maroon. Then he took a step towards the TV, and drew the white brackets. After taking another step, he sketched the maroon bone-shaped area, and added the jagged lines curves in one area of depth. So, the sketch ended up still being a 2D-style sketch, but 3D space was used to organize the different parts of the drawing.

**Learning to use the features of Fabric3D.** The architecture student explored how to use Fabric3D by purposefully trying a different subset of tools for each trial. Not only was this process self-reported in the interviews and in the focus group, but she also focused on specific features per trial. The first trial wasn't anything specific, as she reported, while the second focused on making a simple 2D sheet by tiling fabric squares, ignoring depth. Then, in her third trial, she made a 3D scene of a cylindrical structure, and in her fourth, as shown in figure 4b, she focused on scaling and proportions with the fabric. Her final drawing was a sketch that used all input devices with a variety of different shapes in it, as shown in figure 4c.

*3) Sketches changing over time*

We were unable to find evolutionary trends in sketches alone, besides the use of 3D space in sketches, as described above. The architecture student used different tools during each trial, so we found difficulty finding trends in resulting sketches since the methods and the objects sketched were different.

*4) Satisfaction levels*

Participants reported mild satisfaction with their sketches. In our questionnaire, we asked participants to rate their satisfaction on a five-point scale, with 5 being the most satisfactory, and nine out of fifteen sketches were rated 3, with three out of fifteen sketches rated as 1. The average rating was 2.46.

Participants reported that their sketches were never truly on par with traditional tools, so their satisfaction levels wouldn't be high. The 3D modeler reported some dissatisfaction in making the water bottle in figure 4e, because creating a cylinder using his traditional tools was simple, and to his knowledge, a water bottle was one of the common models to do in introductory

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modeling classes. At the end of trial 3, the architecture student reported that she was familiar with existing tools to easily make walls, but wasn't content that Fabric3D didn't have such a feature.

## VI. Discussion

Several themes emerged from our analysis of the study's results.

### *A. Flexible Input and Playfulness*

We observed a connection between flexible input and playfulness, but the playfulness may have arisen from various factors. The tracking was not ideal, and participants felt they lacked control over the flexible input, so the sketches did not turn out the way participants expected them to. As such, the playfulness attitude may have been a way to deal with these issues, compared to having a predefined, precise idea; users were potentially frustrated that Fabric3D wasn't executing the detailed idea perfectly.

Thus, it proved better for users of Fabric3D to try out broad ideas and see what the resulting sketch looked like, instead of having a detailed idea and getting frustrated at the lack of precision.

There may still be a general relationship between flexible input and playfulness. Even with perfect tracking, it is still difficult to control an entire handkerchief-sized square of fabric simultaneously using only two hands. Fabric is more likely to drape over hands without an underlying sturdy structure.

### *B. 2D versus 3D*

Most of the sketches in our study were 2D sketches, even though Fabric3D was designed for 3D sketches. We think the lack of connection, along with the imperfect tracking, made sketching 3D objects unreliable. Even with the examine mode, participants tended to stay with one perspective camera view, and drew with that view as a 2D canvas.

The examine mode did not support simultaneous sketching, and had we added this feature, users could have looked around and sketched at the same time. We suspect that feature may have made the user more aware of how they were sketching in 3D, and possibly encouraged more 3D sketches.

### *C. Geometric Shapes*

While participants believed that Fabric3D was ideal for neither geometric nor symmetric shapes, the majority of sketches had geometric elements to them, as noted in section 5.2.1. One theory of why this contradiction exists is related to the backgrounds of the participants. The 3D modeler and architecture student were used to modeling tools able to conjure geometric shapes very quickly. The garment designer used measurements to move the block patterns of things like sleeves, which involve controlled movements of lines. These background experiences may have led the participants to sketch geometric shapes with Fabric3D, even though they recognized it was not ideal for this purpose.

### *D. Flexible input as a conceptual tool*

There were many reasons why Fabric3D was regarded as a conceptual tool. Participants noted how rough and unrefined the sketches were, and for very early concept phases of designing, refinement may not matter as much as exploring and brainstorming the idea. Due to the lack of precision of the flexible input, participants may have felt that Fabric3D was great for ideas that were not precise, clear, and predefined.

We believe that this is likely to be inherent to flexible input and 3D sketching. Even if the sketches looked more polished, if Fabric3D had more software features, or if the flexible input could be tracked perfectly, it would still be difficult to design precise surfaces due to the nature of sketching in the air and the difficulty of precisely setting the shape of the flexible input devices. Additionally, fabric's familiarity may make it an effective tool for rapidly brainstorming ideas.

### *E. Designing systems using flexible input*

Designing with flexible input for applications such as surface design proved to be a very challenging problem. Below are some design considerations that we believe had the most impact on the results of this study:

**Tracking method.** Our tracking was vision based, which meant that whenever some of the markers were blocked by occlusion, the system would lose tracking. This may have been the reason why most participants did not mold the fabric, and potentially contributed to flexible input's unreliability. Given this sense of unreliability, participants were potentially encouraged furthermore to just draw imprecise, unrefined 2D sketches.

**Flexible material.** While prior work experimented with other materials [1], the thick plastic leather material and interfacing material still seemed floppy, and participants sensed a lack of control. Users still could not control the entire fabric and move it through the air all at once. So the type of flexible material proved to affect the level of control participants had over the input.

**Software features.** Without the ability to connect elements in sketches, it proved to be difficult to make 3D shapes without them looking distorted. Participants emphasized that an ability to connect sketched elements, along with other additional software features, would improve the system. It was very hard to even draw the outline of a shape, and close the shape by returning to the exact starting point in 3D space.

Software features were also important in 3D sketching as well. Participants found continuous sketching mode to be far more useful than snapshot mode, but this may have been due to our specific software implementation of those features.

**3D interactions.** Selecting 3D sketching as the mode of interaction also proved to be key to our results. With proprioception, we thought that users would be able to use 3D sketching effectively, but this still proved to be difficult. An analogy is to attempt to draw a circle using pencil and paper without looking at the paper and without lifting your pencil. This sort of task becomes even harder when drawing in the air.

## VII. Conclusions and Future Work

We designed a 3D surface design system based on the concepts of flexible input and 3D sketching. By conducting a longitudinal study with surface design experts, we gained insight into the pros and cons of this approach, how flexible input and 3D sketching are used over time, and how to better design such a system.

To address some of the limitations of Fabric3D, we are exploring different kinds of flexible input used in different ways. We are now exploring "posable" input, which is flexible input that holds its own shape after the user molds it. For now, we are embedding aluminum foil inside fabric to give the fabric more rigidity and malleability. This kind of posable input can also be draped over different physical objects to capture shapes in the real world, such as the curve of a chair's armrest, the bevels of a picture frame, or the outline of a computer mouse.

Instead of real-time 3D sketching with flexible input, we are exploring different kinds of interaction that do not suffer from tracking difficulties. One such interaction is a scanning and positioning interaction. Instead of sketching the desired shape in the air in real-time, the interaction starts with first molding the desired shape using the flexible input. Then, the flexible input is scanned into the virtual world, and later manipulated into the desired orientation, position, and scale in virtual 3D space.

We are also considering a subtractive sculpting metaphor for flexible input. Sculptors begin with a block of stone, and subtract from this volume to create the desired shape. Subtractive modeling is already in 3D modeling programs such as Google SketchUp [17]. Future work could build upon existing work that began with a sculpting metaphor for 3D interaction [12].

This paper focuses on the interaction of flexible input, but exploring different kinds of output tools, such as a bigger display Or a head-mounted display may also be worthwhile to aid in the interaction.

The lack of control and unexpected results in using fabric in this study was a disadvantage, but these qualities may be advantageous in more specific art and design domains, just as sketching in the air was suitable in 3D painting applications [2]. For example, garment designers use fabric, which waves and flows in unpredictable ways, so fabric may still be a good input for garment design.

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