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QUICKPROBE: QUICK PHYSICAL PROTOTYPING-IN-CONTEXT USING PHYSICAL SCAFFOLDS IN DIGITAL ENVIRONMENTS

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ABSTRACT

In this paper, we introduce a novel prototyping workflow, *QuickProbe*, that enables a user to create quick-and-dirty prototypes taking direct inspiration from existing physical objects. Our workflow is inspired by the notion of prototyping-in-context using physical scaffolds in digital environments. To achieve this we introduce a simple kinesthetic-geometric curve representation wherein we integrated the geometric representation of the curve with the virtual kinesthetic feedback. We test the efficacy of this kinesthetic-geometric curve representation through a qualitative user study conducted with ten participants. In this study, users were asked to generate wire-frame curve networks on top of the physical shapes by sampling multiple control points along the surface. We conducted two different sets of experiments in this work. In the first set of experiments, users were tasked with tracing the physical shape of the object. In the second set of experiments, the goal was to explore different artistic designs that the user could draw using the physical scaffolding of the shapes. Through our user studies, we showed the variety of designs that the users were able to create. We also evaluated the similarities and differences we observed between the two different sets of experiments. We further discuss the user feedback and the possible design scenarios where our *QuickProbe* workflow can be used.

1 Introduction

1.1 Context & Motivation

Prototyping is a valuable tool in promoting creative idea generation in early design. Lim et al. noted that prototypes can be tools to explore the design space in that they are “*purposefully formed manifestations of design ideas*” [1]. Gerber notes that low-fidelity prototyping affords design practitioners the opportunity to learn from failures thereby providing them confidence in their creative ability [2]. Prototypes have also been viewed as tools for reflection in the early design stages [3]. In fact, the efficacy of low-fidelity prototyping goes as far back as the work by Rudd et al. [4] who noted that the key advantage of low-fidelity prototyping is in supporting the refinements in product requirements and preliminary analysis in the early stages of design.

Despite the increased interest in computational fabrication research to support, enable, and enhance physical prototyping, there are only a handful of tools that bridge the gap between design and prototyping [5]. Much of the prior work in creativity support, typically undertaken in the graphical and HCI communities focuses on purely digital prototyping [6]. To that effect, even much of virtual, augmented, and mixed reality systems for design primarily focus on the creation of the digital artifact [7, 8].

In this paper, we envision a new type of a prototyping workflow, which we call the “*physical-to-digital-to-physical*” workflow for prototyping. The key idea is to enable a user to seamlessly use physical objects within virtual environments in order to design and subsequently fabricate low-fidelity prototypes for exploratory design. This is akin to how we typically make things in real life;

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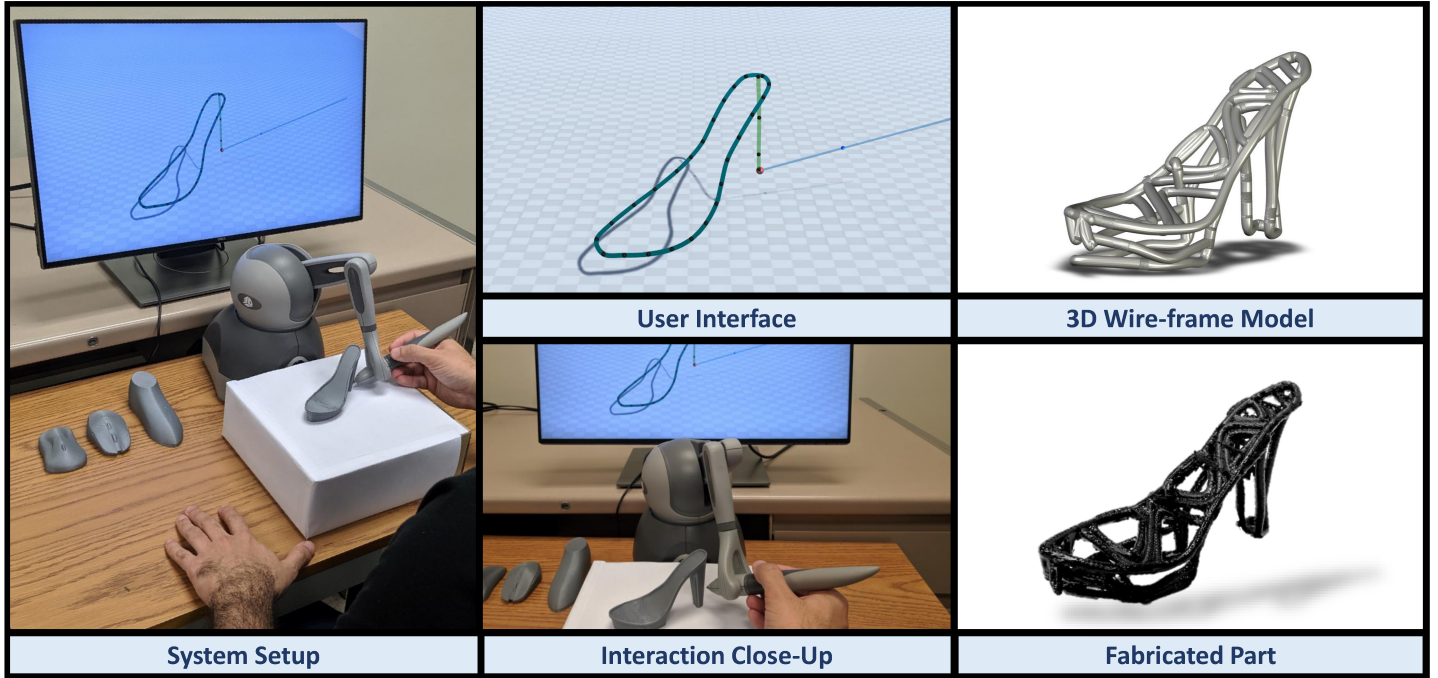


FIGURE 1. General overview of the *QuickProbe* workflow is shown. (Left Column) The complete system setup consists of a haptic device consisting of a stylus, a computer screen, and a physical object attached to an elevated platform. (Middle Column, Top Row) Users get visual feedback of the generated curve-networks in the user interface (UI). (Middle Column, Bottom Row) A close-up of the user interaction with the haptic stylus is shown. Users can create new curves, and add control points by interacting with the buttons present on the haptic stylus. (Right Column, Top Row) 3D Wire-frame model of a user-generated curve network is shown. The wire-frame models are generated using the concept of *sweeps*. (Right Column, Bottom Row) A 3D printed wire-frame model is shown, highlighting the physical prototyping aspect of our workflow.

we design things in context by re-purposing the objects in our vicinity and invent our own use of those things. As a specific instance of this broader principle, we introduce *QuickProbe*, a tangible low-fidelity prototyping workflow that allows a user to interactively draw 3D-printable abstract curve-networks by *directly probing physical objects* serving as tangible proxies.

1.2 Background & Inspiration

There is much recent work on physical prototyping in the design, graphics, and HCI literature. In this work, our specific focus lies in the domain of curve-network prototyping, i.e. the physical production of wire-frame structures as abstract representations of the design concepts. For instance, Peng et al. demonstrated a novel workflow wherein a user could model and edit a wire-frame model that was being simultaneously 3D printed along side the modeling interface. Another intriguing work is *TrussFab*, a system demonstrated Kovacs et al. [9] that builds large-scale structures on desktop printers. Works by Muller’s group on low-fidelity fabrication [10,11] are particularly intriguing in this regard. Specifically, they showcase three different prototyping workflows to demonstrate different levels of abstraction (brick-based, wire-

based, and laser-cut plate-based) in prototyping systems.

Our work is inspired a special class of “*situated*” modeling as well as prototyping frameworks that showcase the utilization of existing objects in the user’s surrounding for getting inspiration for new ideas [12–14]. Further, we also draw upon works that have specifically demonstrated wire-frame and curve design tasks in mixed reality environments, such as *WireDraw* [15], *NapkinSketch* [16, 17]. Finally, we take inspiration from works that highlighted the use of proxies for virtual design tasks. In these, *ProxyPrint* is an excellent example that studies how physical proxies could be leverages for craft activities [18].

1.3 Challenges & Approach

The fundamental challenge we face is that achieving precise spatial manipulation in conventional virtual environments is difficult due to interactions at the arms length. This is critical, especially for prototyping tasks where the user must focus on the creative task rather than being distracted by the lack of spatial control. To address these challenges, our approach in this work is to create a tangible interaction workflow that integrates physical and digital spaces together in order to provide spatial control to

the user during the prototyping task. For this, we present a case where such control can be obtained through direct interaction with the physical objects in close range spaces, known as the peripersonal space.

The key insight behind our approach comes from the fundamental works in ecological psychology, which was spearheaded by Gibson and others in the 60s. The basic premise is that action and perception are intimately connected in close-range spaces (i.e. the peripersonal space) thereby offering immense control in spatial manipulation. Even though this view has been echoed in different forms in recent seminal works on natural user interfaces [19], there is little operational demonstration specifically in the context of low-fidelity prototyping.

We designed, developed, and evaluated our workflow, that we call *QuickProbe* to embody the principles of ecological psychology toward low-fidelity prototyping. To enable a smooth integration between the physical and digital spaces, we develop the idea of *blended haptic feedback* [20, 21] wherein not only is the user able to touch the physical object but simultaneously feel the bending and stretching of the digital curves being created with the proxy in context. To achieve this, we develop the idea of a “kinesthetic curve” that directly leverages the geometric representation of the curve to emulate haptic feedback in the form of stretching and bending the curve.

2 QuickProbe Methodology

We designed an interactive virtual reality (VR) system to do quick prototyping by using physical models of day-to-day objects as scaffolds. In this section, we discuss some fundamental design considerations while designing the interface, system design and implementation, introduce a new *Kinesthetic curve* modelling technique, and explain the interaction workflow.

2.1 Interface Design Considerations

Our physical setup consists of a haptics device to provide kinesthetic feedback, a monitor screen to visualize the actions and a physical object as scaffold. Details about the study setup can be found in Sec: 2.2. Below we discuss some factors that we considered while designing the interface.

1. **Spatial Configuration:** The location of the action space with respect to the body is a key factor while designing the interface. We utilized the action field theory to determine the motor control afforded by the system based on the proximity of the physical object to the user [22]. We designed the interactions such that the actions performed by the user are close to the body. This space is generally referred to as the peripersonal space. Galigani et al. made a note that active tool-usage (haptics stylus in this case) in the user’s peripersonal space enhanced their proxemic perception, allowing for precise control of actions [23]. Hence, using a small space

close to the user’s body gave user a better chance at placing the control points in a precise manner. The haptics device also imposed some physical constraints based on its range of motion. We placed the physical object such that it was close to the user’s body while also keeping it accessible via the haptics stylus. We also used a desk with lower height and a high seating position, giving the user better visibility of the back side of the object.

2. **Feedback:** The system provided three types of feedback: Visual feedback through rendering of the drawn curve, tangible feedback from physically touching the object with the stylus tip, and kinesthetic feedback by the haptics device based on the curve geometry (Sec. 2.3).
3. **Modeling:** The goal of this setup is to enable users to do quick prototyping by using physical objects as scaffolds. We choose curved networks to model the prototypes because they would use lesser time and material to manufacture. To increase the speed of prototyping, we choose to sample points on the surface of the physical object rather than drawing continuous curves.

2.2 System Setup and Implementation

Our experimental setup (Fig. 1) comprised of a 3D Systems Touch haptics device capable of providing a maximum force of 3.3 N. An Alienware 15R3 laptop computer with an Intel Core i7 – 7700HQ CPU (2.6GHz), 16GB of GDDR5 RAM, and a NVIDIA GeForce GTX2070 graphics card, running 64-bit Windows 10 Professional Operating System was used. Our application was developed in the Unity3D game engine using the 3D Systems Openhaptics® Unity plugin. The application was mirrored on a monitor screen. The participants used four different 3-D printed models as a base to draw curves by sampling control points on the surface of these models. Since the 3-D printed models were not tracked in the physical space, they were fixed on top of a rigid base which was in turn fixed on a table. The position of the haptics device was also fixed on the table, making sure that the orientation and position of the models didn’t change with respect to the haptics device during the study. Specific positions and orientations for fixing the models were chosen that afforded easy accessibility around the entire model while probing with the haptics stylus. In this preliminary setup, the visual and kinesthetic spaces are not co-located. Hence, the visual rendering is on the screen, but the physical action is done near the body. We believe that in this setup, the lack of co-location of the action and visual spaces is compensated by a strong tangible connection to the physical object.

2.3 “Kinesthetic-Curve” Modeling

In order to enhance the controllability of the curve during mid-air interactions, we provide kinesthetic feedback constrained by the curve geometry. Work by Ronak et al. [24], showed the role

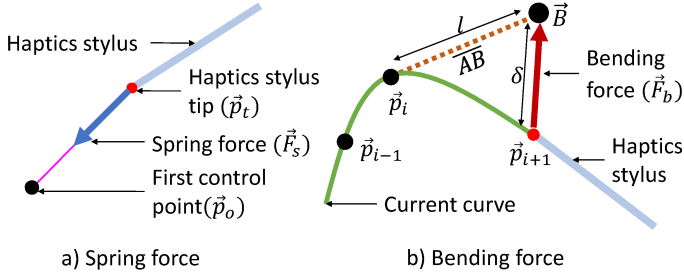


FIGURE 2. An illustration of the spring force (a) and bending force (b) experienced by the user.

of kinesthetic feedback for drawing 3D curves on planar surfaces and their 3D rotations. Providing kinesthetic force to guide curve creation in virtual environments enhance the user performance as explored in some of the earlier works by Wacker et al. [25] who studied the effects of providing surface and line guidance to users to virtually sketch/trace on physical objects and compared that to sketching on virtual objects. Machuca et al. [26] also provided smart 3D guides to help users improve their 3D virtual sketches. In another work by Panda et al. [27] developed morphable surfaces to provide tangible feedback to users while sketching on top of virtual objects in VR. Inspired from prior works, we introduce a new idea called a *kinesthetic curve* which is an integrated representation of the geometry and the haptics. The key idea is that the nature of the feedback is inherent in (and therefore constrained by) the fundamental geometric representation of the curve. In this work, we specifically show an instance of this idea through the Catmull-Rom curve representation [28]. Catmull-Rom splines are a family of cubic interpolating splines. They are a special case of cubic Hermite splines. The general equation of the Catmull-Rom spline between two points p_0 and p_1 is as follows:

$$p(t) = (2t^3 - 3t^2 + 1)p_0 + (t^3 - 2t^2 + t)m_0 + (-2t^3 + 3t^2)p_1 + (t^3 - t^2)m_1 \quad (1)$$

where t lies in the interval $(0, 1)$. m_0 and m_1 are evaluated as follows:

$$m_k = \frac{1}{2} \frac{p_{k+1} - p_{k-1}}{x_{k+1} - x_{k-1}} \quad (2)$$

The Catmull-Rom spline was chosen because it ensures that the interpolated curve passes through the control points p_0 and p_1 while maintaining C^1 continuity, which in this case is defined by the user.

As soon as the first control point is defined, the haptics device starts providing a spring force feedback (\vec{F}_s), which is directly proportional to the distance between the current haptics stylus tip

position (\vec{p}_t) and the first control point (\vec{p}_0) (Fig. 2(a)).

$$\vec{F}_s = -K_s(\vec{p}_t - \vec{p}_0) \quad (3)$$

The spring constant K_s was set to be 0.35, based on some initial testing. Since we need at least three control points in order to generate a Catmull-Rom splines, the system displayed a straight line segment joining the first control point and the haptics stylus tip. Once the subsequent control points are defined, the system displayed a Catmull-Rom spline joining all the control points and the stylus tip. We introduced a bending force (\vec{F}_b) in the kinesthetic feedback if the number of defined control points was greater than two. This bending force was calculated based on the metaphor of force required to bend a metal wire. This metal wire was modelled as a straight circular cantilever beam whose one end (fixed end) was fixed at the last defined control point (\vec{p}_i) and the other end (free end) was attached to the stylus tip (\vec{p}_{i+1}) which moved in 3D space (Fig 2(b)). As the stylus tip moved in space, the bending force (\vec{F}_b) and spring force (\vec{F}_s) changed dynamically. The steps for calculating the bending force are as follows:

1. Compute the length of the Catmull-Rom spline (l) between \vec{p}_{i+1} and \vec{p}_i . This was considered as the length of the cantilever beam being deformed.
2. Draw a line segment \overline{AB} of length l originating at \vec{p}_i along the tangent at \vec{p}_i in the direction of \vec{p}_{i+1} .
3. Calculate the distance (δ) between the free end (\vec{B}) of \overline{AB} and \vec{p}_{i+1} . This can be considered as the deflection of the cantilever beam \overline{AB} .
4. Calculate \vec{F}_b according to the following equation:

$$\vec{F}_b = K_b \frac{\delta}{l^3} \hat{n} \quad (4)$$

where $K_b = 0.35$ is a constant based on the initial testing and \hat{n} is the unit vector along the line joining the free end of \overline{AB} and \vec{p}_{i+1} .

$$\hat{n} = \frac{\vec{p}_{i+1} - \vec{B}}{\|\vec{p}_{i+1} - \vec{B}\|} \quad (5)$$

Hence, the kinesthetic feedback provided for generating the curves was a combination of two forces \vec{F}_b and \vec{F}_s , where \vec{F}_s is present only while inserting the second control point.

2.4 Tangible Interaction Workflow

There are two key tangible interaction modes in our prototyping workflow, namely, searching and probing.

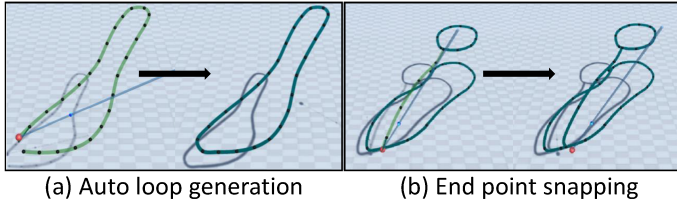


FIGURE 3. (a) The open-ended curve is transformed into a loop if its end points are less than a certain distance apart. (b) The end points of the current curve snaps on to the nearest points on the existing curve.

- **Searching:** The searching mode is defined as the instance where the user visually inspects the physical part and takes creative decisions on how to develop the geometry.
- **Probing:** Probing mode is defined as the instance when the user is in the process creating the prototype based on the decisions taken in the searching phase. This mode is a combination of the direct physical interaction that the user has with the physical object as well as our kinesthetic-curve that the user is drawing. We use the metaphor of probing since the user is "drawing" the kinesthetic-curve by sampling multiple points along the surface of the physical object using the haptic stylus as a probe.

In order to create kinesthetic curves, we utilize the two buttons present on the haptics stylus, namely the forward and the back button. The user starts drawing the curve by clicking the forward button. This adds a control point at the stylus tip position on the time of the click. This also activates the kinesthetic feedback. Then the user moves the stylus to another location where he/she wants to add another control point. On moving the stylus to the desired position, the user clicks the forward button to add another control point. This way, the user creates the desired number of control points. The user can press the back button to stop drawing the current kinesthetic-curve, which also deactivates the kinesthetic feedback. The user then repeats the process multiple times as desired (Fig: 4).

2.5 3D Wire-frame Model Generation for Prototyping

In addition to enabling the creation of virtual curve networks, an important aspect of our *QuickProbe* workflow is to allow quick prototyping of these curve networks. In order to create a geometric representation of these networks that is amenable to prototyping, which in our case is 3D printing, we adopt 'sweeps' as our geometric modeling technique. Sweeps constitute three main types of curves - the profile (sectional shape), the path, and the guide curve. In our specific case, we want the physical prototype to closely resemble the virtual curve networks created by the users, hence, forming a wireframe model. To construct this representation, we define the profile to be a circular curve; the path to be the individual curves present in the curve network; and the guide

curve to be a constant scaling function for the profile. Sweeps, therefore, allow a straightforward way to geometrically represent the curve networks, and can provide the necessary mesh information for 3D printing. In order to make the process of creating the 3D wireframe models more convenient for users, we provide the users with two specific features:

- The first feature was the ability to create closed loops using the closed Catmull-Rom splines. To draw a closed loop curve, the user started by drawing an open-ended curve matching the loop using the workflow described above. On exiting the sketch (by pressing the back button on haptics stylus), the application checked the distance between the end points of this new open-ended kinesthetic curve and if that distance was less than a certain range (0.6 units), the loop was closed by recomputing the Catmull-Rom spline and adding a section joining the end points (Fig: 3(a)).
- The second feature was the automatic snapping of the end points of an open-ended curve to the nearest point on any of the previously drawn kinesthetic curve (Fig: 3(b)). Specifically, if the distance between the end points of the drawn open-ended curve is more than the threshold for closing the curve (0.6 units), then each end point of the current curve would be replaced with their respective nearest point on any of the existing curves.

3 Experiment Design

Our experiments were designed with the goal of enabling users to create quick prototypes using our *QuickProbe* workflow. As a result, we conducted two sets of experiments that focused on the qualitative nature of the workflow. In the first experiment, users were asked to create kinesthetic curve networks on the surface of 3D printed objects. The objective here was to observe how users created different types of curve networks on surfaces of objects belonging to the same class (i.e., different types of computer mice and different types of shoes). The second experiment was designed to observe how users generated *artistic patterns* using curve networks on the 3D printed objects, that served as physical scaffolds.

3.1 Participants

We recruited 10 participants (7 male, 3 female)(5 per experiment) enrolled in undergraduate and graduate degrees across the university. The participants belonged to the age group of 18-26 years with backgrounds in engineering and biomedical sciences. Participants had no prior experience with sketching in virtual interfaces and in using haptic devices. We also made sure that the participants did not suffer from any physical conditions that could affect their designing sessions.

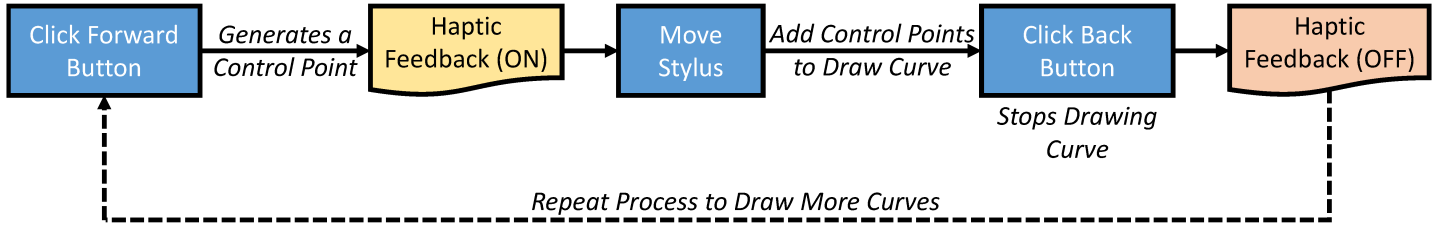


FIGURE 4. Flowchart showing specific user-interactions with the haptic stylus to create curves and add control points. The flowchart also highlights the activation and de-activation of the haptic feedback within the interaction workflow.

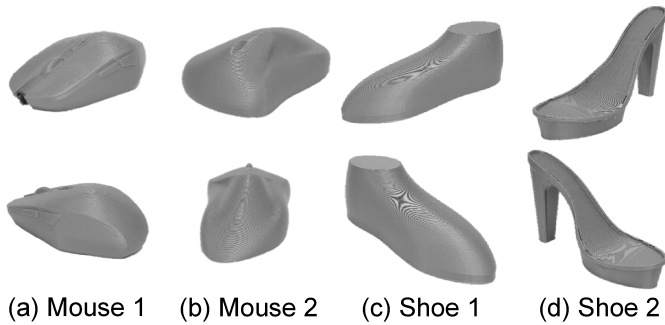


FIGURE 5. 3D printed proxies of physical objects used as physical scaffolds in the user studies are shown from different angles. These include: (a) Mouse 1, (b) Mouse 2, (c) Shoe 1 and, (d) Shoe 2.

3.2 Procedure

Each user study lasted between 35 to 50 minutes. As our user studies were split into two experiments, we first describe the common elements across both sets of studies. Both studies started with the participants filling a demographic questionnaire and a short pre-screening interview asking for their prior experience with sketching and designing in virtual interfaces and any experience with haptic devices. The participants were then given a short tutorial on the user interface elements and the basic interactions that were afforded by the interface. Next, we describe the experiment specific tasks that the participants performed.

Experiment 1

1. **Practice:** Participants were given 2 – 3 minutes to practice generating curves using the haptic device and visualizing the curve generation in the user interface. The participants were encouraged to ask questions and clarify any doubts they had regarding the curve-generation process.
2. **Trials:** After the practice session, the participants were given the task of generating curve networks on the surface of four 3D printed objects, i.e., two computer mice and two shoes (Figure. 5). There were no time-based restrictions, however, the participants were allowed to make only one curve net-

work for each object. The participants were also asked to keep the fabrication process (in our instance 3D printing) in mind while creating their curve networks, and as such, were discouraged from generating curves in mid-air (i.e., without any supports).

Experiment 2

1. **Practice:** For this experiment, participants were given 4 – 5 minutes to practice generating patterns using curve-networks on a randomly selected ‘mouse’ object 5. Similar to the first experiment, participants were encouraged to clarify any doubts they had regarding the system.
2. **Trials:** After the practice session, participants were shown examples of ‘artistic curve patterns’ from prior works [29]. They were then asked to create two sets of curve-network patterns using each 3D printed shoe as a physical scaffold (a total of 4 curve-networks per participant). The participants were given around 15 minutes to create two patterns per shoe and were not restricted in the kinds of patterns they could generate. However, similar to *Experiment 1*, participants were asked to keep the fabrication process in mind while generating their curve networks.

At the end of each user study, participants were given a post-study questionnaire that included surveys to assess the creativity support offered by our *QuickProbe* system [30], the usability of our system [31] and study specific questions to elicit the participants’ general feedback on their experience with the workflow.

3.3 Data Collected

For each study session we collected a wide variety of data that included: (a) screen recording of the interface, (b) video recording of the participants’ use of the haptic device, (c) curve-network specific time-stamped data such as - the control points of the Catmull-Rom splines, interpolated points, stylus tip positions and the haptic stylus button press events.


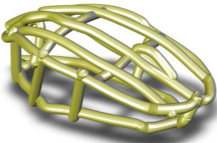
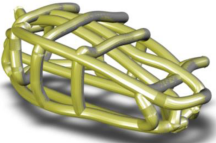
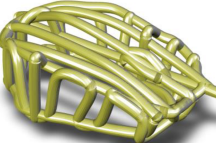
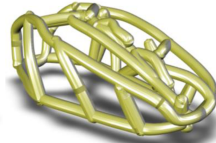
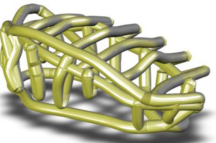
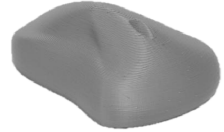

















	User 01	User 02	User 03	User 04	User 05
	 Minutes Taken: 3.6 Number of Curves: 15	 Minutes Taken: 3.54 Number of Curves: 7	 Minutes Taken: 9.99 Number of Curves: 17	 Minutes Taken: 6.76 Number of Curves: 18	 Minutes Taken: 5.02 Number of Curves: 25
	 Minutes Taken: 3.48 Number of Curves: 13	 Minutes Taken: 3.53 Number of Curves: 7	 Minutes Taken: 10.36 Number of Curves: 19	 Minutes Taken: 6.27 Number of Curves: 14	 Minutes Taken: 2.89 Number of Curves: 13
	 Minutes Taken: 4.67 Number of Curves: 13	 Minutes Taken: 3.31 Number of Curves: 11	 Minutes Taken: 9.62 Number of Curves: 29	 Minutes Taken: 4.44 Number of Curves: 11	 Minutes Taken: 3.37 Number of Curves: 13
	 Minutes Taken: 4.29 Number of Curves: 21	 Minutes Taken: 3.89 Number of Curves: 20	 Minutes Taken: 14.24 Number of Curves: 25	 Minutes Taken: 6.94 Number of Curves: 20	 Minutes Taken: 5.36 Number of Curves: 33

FIGURE 6. All renderings of the scaffolds that the users created are shown for experiment 1. For the first experiment each participant was asked to draw curves on four different objects. No time limits were imposed but the number of curves and time taken were recorded for each object. Additionally the object being modeled is shown (Left Column).

4 Results and User Feedback

We recorded 40 trials in total across the two experiments. In the following sub-sections, we will share the results and findings of these trials and perform a qualitative analysis of the user feedback based on the Creativity Support Index (CSI) [30] and the System Usability Scale (SUS) [31].

We collected the 3D wire-frame networks generated by each user for each trial. Each wire-frame network model consisted of multiple kinesthetic curves. Taking the path as the kinesthetic curves and the profile as a uniform circular cross-section, we generated the sweeps for each wire-frame network using MATLAB and generated .ply files. These sweeps were then rendered using Meshlab and Solidworks eDrawings. We also 3D printed the wire-frame models of 5 mice and 5 shoes from experiment 1

and we printed 1 wire-frame per-shoe per-user for experiment 2 (Fig.8).

Experiment 1 The wire-frame models generated in each trial for experiment 1 were rendered and are shown in Fig:6. We saw a wide range of values for the amount of time taken and the number of curves drawn by each user across different shapes, with the highest number of curves in Shoe-2 except for User-03. This maybe due to the complex geometry of the Shoe-2. However, the time taken for Shoe-2 across a given user didn't follow this pattern. We now report some of the common as well as unique patterns that we observed during the trials. We observed a few common patterns among different users. Each user started the wire-frame network by drawing a closed curve at the base of the


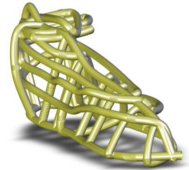

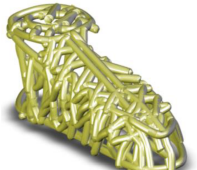
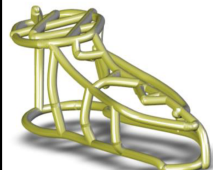
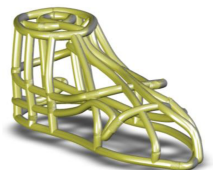
















	User 06	User 07	User 08	User 09	User 10
	 Number of Curves: 11 Number of Points: 118	 Number of Curves: 16 Number of Points: 213	 Number of Curves: 51 Number of Points: 417	 Number of Curves: 21 Number of Points: 90	 Number of Curves: 18 Number of Points: 125
	 Number of Curves: 10 Number of Points: 246	 Number of Curves: 35 Number of Points: 221	 Number of Curves: 48 Number of Points: 579	 Number of Curves: 18 Number of Points: 69	 Number of Curves: 19 Number of Points: 99
	 Number of Curves: 15 Number of Points: 187	 Number of Curves: 24 Number of Points: 194	 Number of Curves: 33 Number of Points: 324	 Number of Curves: 15 Number of Points: 91	 Number of Curves: 26 Number of Points: 137
	 Number of Curves: 17 Number of Points: 189	 Number of Curves: 22 Number of Points: 226	 Number of Curves: 36 Number of Points: 340	 Number of Curves: 22 Number of Points: 120	 Number of Curves: 19 Number of Points: 108

FIGURE 7. All renderings of the scaffolds that the users created are shown for experiment 2. For the second experiment each participant was asked to draw two different curves for two different objects for a total of 4 scaffolds. The users were given a time limit of 15 minutes to create the two scaffolds for one object for a total time of 30 minutes.

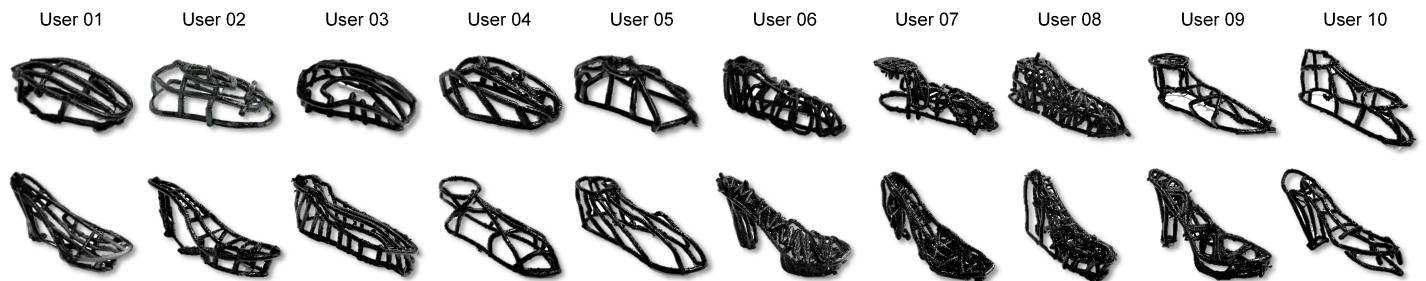


FIGURE 8. The 3D printed samples of the sketched curve. Every user had two of their sketches chosen at random and then 3D printed using a Prusa i3 MK3S+ printer using PLA filament.

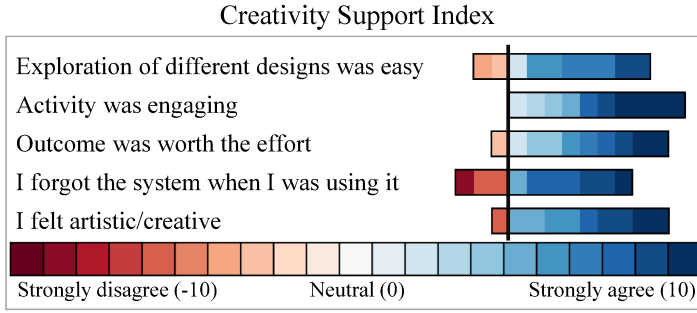


FIGURE 9. User feedback on the creativity support offered by the *QuickProbe* workflow using the Creativity Support Index. Overall feedback for our system was positive. Most participants could easily explore different designs and felt the activity was engaging.

physical objects and then started to work from the top part of the shapes. Each user generated the curves of varying lengths while drawing the wire-frames. For User-05 and Shoe-01, we saw an interesting pattern of the wire-frame with the curves flowing from the bottom of the shoe to the top.

Experiment 2 The renderings of the wire-frame models generated in each trial for experiment 2 are shown in Fig:7. The number of curves drawn by each user in experiment-2 were comparable to those of experiment-1 for the shapes of same class. However, we observed a denser wire-frame with longer kinesthetic curves. We believe that the longer kinesthetic curves with multiple control points helped users to draw smooth but dense patterns on top of the physical shapes. User-06, User-07, and User-08 used a zig-zag pattern to *decorate* their wire-frame models. User-09 used a unique pattern of multiple closed loop curves with three control points to decorate the Shoe-2. The number of control points per shoe type were generally higher as compared to experiment-1. as observed in experiment-1, the users started the wire-frame network by drawing a closed-loop kinesthetic curve at the base of the physical scaffolds.

4.1 User Feedback

The user feedback for our *QuickProbe* workflow was generally positive. The participants' response to the Creativity Support survey (CSI) (Figure. 9) showed that users found our system to be engaging while making them feel artistic. Most participants also felt that our system allowed them to explore different designs easily, and felt that their design outcomes were worth the effort. While the overall feedback in the CSI survey was positive, we did have a few participants who felt that it was hard for them to explore different designs and that our system did not necessarily make them feel artistic. Some of the reasons that these users cited were in relation to the lack of rotation of the physical objects, unintended addition of control points and fatigue during

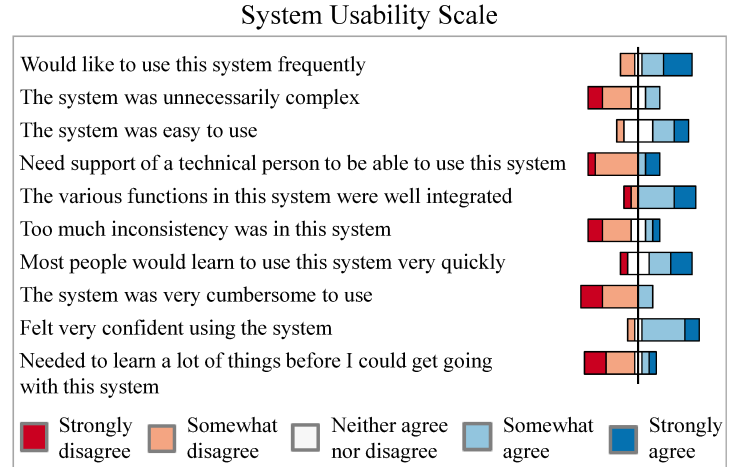


FIGURE 10. User feedback on the usability of our *QuickProbe* system using the System Usability Scale.

the experiments. While the lack of rotation was done to prevent the objects from containing trackers protruding from the surface of the objects, we do recognize other methods, such as digital fly-wheels, that could enable rotation for future implementations of our workflow. In regards to the addition of control points, we mainly added this constraint in order to prevent users from generating mid-air curve networks that could not be fabricated. In an interface targeted purely towards generating curve-networks for digital environments, this constrain could easily be removed. The fatigue aspect of the study could be alleviated with a better framework for haptic feedback. A study could be done to optimize the spring stiffness value K_s , and the bending constant K_b in order to improve the rendering of the haptics feedback that could reduce fatigue. Haptic snapping onto a desired curve could also improve the haptics feedback. In its current form, our haptic feedback was noticed by most participants and had mixed reviews. While some participants liked the feedback while creating curves, others either did not notice much effect or found the feedback to be a limiting factor while creating free-form and sharp curves. An improved framework for the haptics feedback can certainly benefit curve-network generation. We also note that users did not necessarily forget that they were using our system. A major reason for this could be that the nature of our workflow expected the users to be aware of the location of the stylus not just in the real world but also in the virtual interface.

Apart from the Creativity Support survey, users also provided feedback on the usability of our system (Figure. 10). Majority of the participants felt very confident while using our system and felt that most people could learn the system quickly. Participants also noted that they did not need to learn a lot of things before being able to use the system and that they could manage to use the system without the help of a technical person. Similar to the CSI

survey, a few users did highlight their issues with the system in the survey. Some of the system specific issues they mentioned were the lack of a delete and undo feature, the ability of not moving the pen more freely, and the lack of a rotation option in the virtual interface. We believe that these features could be easily integrated into future iterations of the workflow to make it more user-friendly. In addition to these surveys, we also collected general feedback from the participants regarding their experience using our system, and these were generally positive. One participant said *“This was a very interesting and new experience that I would like to learn more about. The movements were new and intriguing and I enjoyed visualizing my work right in front of me on the computer”* while another mentioned *“It was really smooth. One complaint I had was when I made the error point the system tried to pull me towards that point for the next point. Other than that, very smooth interface and I would recommend it to others.”* Overall, the feedback we received from participants were detailed and constructive.

5 Limitations & Future Work

Our study revealed some important design considerations for future systems which can help achieve the broader goal of this research i.e. prototyping in context. We designed this system to help users create quick wire-frame prototypes by using physical shapes as scaffolds. In this section we will discuss some of the limitations of the existing system that we discovered during the research and the scope for future systems. Since the objects used as scaffolds were not tracked in the physical space, the user could not rotate them to manipulate the view, change orientation, and draw on the bottom part of the shapes. This limits the types of designs a user would be able to create using this system. By tracking the physical object, the user would be able to create kinesthetic curves bi-manually. Another limitation of this system is that the visual space and action space are not co-located. In future systems, we would like to render the kinesthetic curves directly on top of the physical object or render the physical object in the virtual display, in order to co-locate both these spaces. This would help enhance the blending of visual and tactile feedback. With regards to the system workflow, an editing mode is required so that the user could edit the existing 3D wire-frame network prototypes and refine them as desired. Different haptics feedback for editing could be rendered in order to aid with the overall design process. When asked for some future use cases, the users suggested that this system could be used to model digital objects in AR/VR applications, educating children about rapid prototyping by using a gamified approach, perform FEA analysis using the haptics device, and reverse engineer a product to refine certain elements.

6 Conclusion

Our main goal in this work was to enable users to create quick-and-dirty prototypes using direct inspiration from physical objects. Our motivation for the work stemmed from the notion of prototyping-in-context. In order to enable this, we developed a novel workflow, *QuickProbe* that used a kinesthetic-geometric curve representation to allow users to create curve networks using real world objects as physical scaffolds. Using our *QuickProbe* workflow users could create virtual curve-networks by taking inspiration from physical objects. The curve-networks were then geometrically represented as 3D wire-frame models using the concept of *sweeps*. The 3D geometric representations were then used to fabricate the prototypes created by users. In order to understand how users interacted with our workflow we conducted two sets of user studies with a total of 10 participants. Our first study was focused on understanding how users created different curves networks for objects belonging to the same class(i.e., computer mice and shoes). Our second study focused on understanding how participants used our workflow to create artistic-curve networks on the physical scaffolds. Through our user studies we showed a variety of designs that the participants created. We also showed the 3D printed prototypes developed by participants. We further discussed how our workflow could be used in specific designing scenarios.

REFERENCES

- [1] Lim, Y.-K., Stolterman, E., and Tenenber, J., 2008. “The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas”. *ACM Trans. Comput.-Hum. Interact.*, **15**(2), July, pp. 7:1–7:27.
- [2] Gerber, E., and Carroll, M., 2012. “The psychological experience of prototyping”. *Design Studies*, **33**(1), pp. 64 – 84.
- [3] Hartmann, B., Klemmer, S. R., Bernstein, M., Abdulla, L., Burr, B., Robinson-Mosher, A., and Gee, J., 2006. “Reflective physical prototyping through integrated design, test, and analysis”. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology, UIST '06*, ACM, pp. 299–308.
- [4] Rudd, J., Stern, K., and Isensee, S., 1996. “Low vs. high-fidelity prototyping debate”. *interactions*, **3**(1), Jan., pp. 76–85.
- [5] Weichel, C., Lau, M., Kim, D., Villar, N., and Gellersen, H. W., 2014. “Mixfab: A mixed-reality environment for personal fabrication”. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems, CHI '14*, ACM, pp. 3855–3864.
- [6] Shneiderman, B., 2007. “Creativity support tools: Accelerating discovery and innovation”. *Communications of the ACM*, **50**(12), pp. 20–32.

- [7] Wang, G. G., 2002. "Definition and review of virtual prototyping". *J. Comput. Inf. Sci. Eng.*, 2(3), pp. 232–236.
- [8] Gibson, I., Gao, Z., and Campbell, I., 2004. "A comparative study of virtual prototyping and physical prototyping". *International journal of manufacturing technology and management*, 6(6), pp. 503–522.
- [9] Kovacs, R., Seufert, A., Wall, L. W., Chen, H.-T., Meinel, F., Müller, W., You, S., Kommana, Y., and Baudisch, P., 2017. "Demonstrating trussfab: Fabricating sturdy large-scale structures on desktop 3d printers". In Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems, CHI EA '17, ACM, pp. 445–448.
- [10] Mueller, S., Im, S., Gurevich, S., Teibrich, A., Pfisterer, L., Guimbretière, F., and Baudisch, P., 2014. "Wireprint: 3d printed previews for fast prototyping". In Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology, UIST '14, ACM, pp. 273–280.
- [11] Mueller, S., Beyer, D., Mohr, T., Gurevich, S., Teibrich, A., Pfisterer, L., Guenther, K., Frohnhofen, J., Chen, H.-T., Baudisch, P., Im, S., and Guimbretière, F., 2015. "Low-fidelity fabrication: Speeding up design iteration of 3d objects". In Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems, CHI EA '15, ACM, pp. 327–330.
- [12] Lau, M., Hirose, M., Ohgawara, A., Mitani, J., and Igarashi, T., 2012. "Situating modeling: A shape-stamping interface with tangible primitives". In Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction, TEI '12, Association for Computing Machinery, p. 275–282.
- [13] Chen, X. A., Coros, S., Mankoff, J., and Hudson, S. E., 2015. "Encore: 3d printed augmentation of everyday objects with printed-over, affixed and interlocked attachments". In Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, UIST '15, ACM, pp. 73–82.
- [14] Huo, K., Vinayak, and Ramani, K., 2017. "Window-shaping: 3d design ideation by creating on, borrowing from, and looking at the physical world". In Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction, TEI '17, Association for Computing Machinery, p. 37–45.
- [15] Yue, Y.-T., Zhang, X., Yang, Y., Ren, G., Choi, Y.-K., and Wang, W., 2017. "Wiredraw: 3d wire sculpturing guided with mixed reality". In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, CHI '17, ACM, pp. 3693–3704.
- [16] Buchmann, V., Violich, S., Billingham, M., and Cockburn, A., 2004. "Fingertips: Gesture based direct manipulation in augmented reality". In Proceedings of the 2Nd International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia, GRAPHITE '04, ACM, pp. 212–221.
- [17] Xin, M., Sharlin, E., and Sousa, M. C., 2008. "Napkin sketch: Handheld mixed reality 3d sketching". In Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology, VRST '08, ACM, pp. 223–226.
- [18] Torres, C., Li, W., and Paulos, E., 2016. "Proxyprint: Supporting crafting practice through physical computational proxies". In Proceedings of the 2016 ACM Conference on Designing Interactive Systems, DIS '16, ACM, pp. 158–169.
- [19] Regazzoni, D., Rizzi, C., and Vitali, A., 2018. "Virtual reality applications: guidelines to design natural user interface". In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 51739, American Society of Mechanical Engineers, p. V01BT02A029.
- [20] Robles-De-La-Torre, G., and Hayward, V., 2001. "Force can overcome object geometry in the perception of shape through active touch". *Nature*, 412(6845), pp. 445–448.
- [21] Schraffenberger, H., and van der Heide, E., 2016. "Multimodal augmented reality: The norm rather than the exception". In Proceedings of the 2016 Workshop on Multimodal Virtual and Augmented Reality, MVAR '16, ACM, pp. 1:1–1:6.
- [22] Bufacchi, R. J., and Iannetti, G. D., 2018. "An action field theory of peripersonal space". *Trends in cognitive sciences*, 22(12), pp. 1076–1090.
- [23] Galigani, M., Castellani, N., Donno, B., Franza, M., Zuber, C., Allet, L., Garbarini, F., and Bassolino, M., 2020. "Effect of tool-use observation on metric body representation and peripersonal space". *Neuropsychologia*, 148, p. 107622.
- [24] Mohanty, R. R., Castillo, R. M., Ragan, E. D., and Krishnamurthy, V. R., 2020. "Investigating force-feedback in mid-air sketching of multi-planar three-dimensional curves". *Journal of Computing and Information Science in Engineering*, 20(1), p. 011010.
- [25] Wacker, P., Wagner, A., Voelker, S., and Borchers, J., 2018. "Physical guides: an analysis of 3d sketching performance on physical objects in augmented reality". In Proceedings of the Symposium on Spatial User Interaction, pp. 25–35.
- [26] Machuca, M. D. B., Stuerzlinger, W., and Asente, P., 2019. "Smart3dguides: Making unconstrained immersive 3d drawing more accurate". In 25th ACM Symposium on Virtual Reality Software and Technology, VRST '19, Association for Computing Machinery.
- [27] Panda, P., Ho, C., and Ham, D., 2021. "Morphaces: exploring morphable surfaces for tangible sketching in vr". In Creativity and cognition, pp. 1–1.
- [28] Catmull, E., and Rom, R., 1974. "A class of local interpolating splines". In *Computer aided geometric design*. Elsevier, pp. 317–326.
- [29] Zehnder, J., Coros, S., and Thomaszewski, B., 2016. "De-

- signing structurally-sound ornamental curve networks”. *ACM Transactions on Graphics (TOG)*, **35**(4), pp. 1–10.
- [30] Cherry, E., and Latulipe, C., 2014. “Quantifying the creativity support of digital tools through the creativity support index”. *ACM Transactions on Computer-Human Interaction (TOCHI)*, **21**(4), pp. 1–25.
- [31] Brooke, J., 1996. “Sus: a “quick and dirty’usability”. *Usability evaluation in industry*, **189**(3).