Enhancing VR Sketching with a Dynamic Shape Display

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ABSTRACT

Sketching on virtual objects in Virtual Reality (VR) can be challenging due to the lack of a physical surface that constrains the movement and provides haptic feedback for contact and movement. While using a flat physical drawing surface has been proposed, it creates a significant discrepancy between the physical and virtual surfaces when sketching on non-planar virtual objects. We propose using a dynamic shape display that physically mimics the shape of a virtual surface, allowing users to sketch on a virtual surface as if they are sketching on a physical object's surface. We demonstrate this using VRScroll, a shape-changing device that features seven independently controlled flaps to imitate the shape of a virtual surface automatically. Our user study showed that participants exhibited higher precision when tracing simple shapes with the dynamic shape display and produced clearer sketches. We also provided several design implications for dynamic shape displays aimed at enabling precise sketching in VR.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**.

KEYWORDS

on-surface interactions, dynamic shape display, virtual reality

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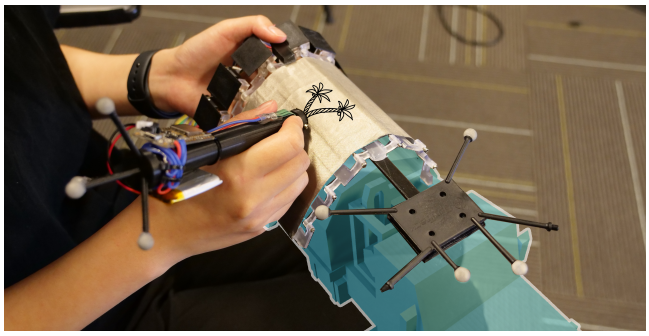


Figure 1: A shape-changing surface that mimics the surface of a virtual object can facilitate physical interactions, such as friction, constrained movement, and haptic feedback, allowing users to create more precise and smooth sketches.

1 INTRODUCTION

Leveraging spatial perception and 6-DOF manipulation, virtual reality environments provide designers with an immersive platform for 3D model interaction [3, 25]. Although typical mid-air interaction methods, such as using controllers and hands, facilitate fluid manipulations, they may not be able to support the natural and precise on-surface interactions essential for design tasks such as fine-line drawing [5]. This limitation stems from the lack of resistance and tactile feedback provided by physical contact, which is critical for accurately perceiving and manipulating virtual geometry [24].

To improve the performance of VR sketching, previous research has incorporated virtual surfaces with flat plates or tablets, which can rest the user's hands, guide pen movement, and prevent strokes from penetrating or leaving the virtual surface [4, 5, 12, 13, 44, 48]. However, utilizing planar surfaces to represent non-planar shapes, including architectures, creatures, and characters, can be challenging because of the incongruities of their geometric features. While some systems enable interactions on non-planar surfaces by projecting the virtual surface on a touchscreen [13, 17] or a graphic tablet [4, 12, 29], the absence of geometry information, and the discrepancy between the tablet and the virtual shape might results in unintuitive [36], technically challenging, and learning-demanding [4, 6] design process in VR. 3D-printed physical proxies that exactly replicate a virtual object have also been exploited to improve drawing performance [48]. However, it may be impractical to fabricate such proxies for the diverse virtual objects users may interact with in VR.

To tackle this challenge of enabling precise sketching on virtual objects with various shapes, we propose using a dynamic shape-changing surface that can mimic the shape of virtual object surfaces. Many shape-changing devices, also known as shape displays, have been developed and shown to be effective for immersive in-hand interactions in VR [8, 20, 31, 39, 45, 49], however, their effectiveness in supporting precise interactions, such as sketching, has rarely been studied. To investigate how using a shape-changing device affects the precision, quality, and usability of sketching in VR, we developed *VRScroll*, a scroll-like dynamic shape display (Figure 1). VRScroll consists of seven 3D-printed flaps that are controlled by DC motors to form a surface that mimics the surface of a virtual object in VR. We conducted a user study to understand the effect of having a physical surface using a dynamic shape display by comparing it with in-air sketching on planar and non-planar surfaces. The results showed that the participants could more precisely

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trace simple shapes and make smoother strokes. The free-form sketches participants made with VRScroll were rated to be clearer by Amazon Mechanical Turk workers. The participants also found sketching with VRScroll felt more realistic and natural.

In summary, the main contributions of this work include the design and implementation of VRScroll, a shape-changing device developed to support precise on-surface interactions, and the results from a user study that investigates the effect of a physical surface on the sketching performance on various surfaces.

2 RELATED WORK

2.1 Sketching in VR

VR technology has facilitated the creation of an immersive and intuitive workspace for 3D design [3, 25], where on-surface interaction is an essential and fundamental task. Direct 3D sketching and model manipulation using VR technology has received considerable attention in both academic research [25, 27, 56] and commercial applications such as Tilt Brush by Google [1]. Immersive environments can benefit designers with good spatial perception, high DOF pen interaction, fast and easy model manipulation, and creative and expressive design exploration. However, VR sketching has been observed to result in significantly lower precision and shape refinement as compared to conventional 2D sketching on a tablet [36], primarily due to a lack of precise control in mid-air [24, 26].

To enhance users' VR sketching performance, researchers have explored the integration of haptic devices into virtual environments [5]. For example, steering pen movement by a haptic device [26] or simulating different surfaces using in-hand pneumatic and vibrotactile haptic feedback [15]. While haptic devices can provide users with tactile and force feedback, they fail to replicate the sensation of pen contact and the physical support on a sketching board, which may affect sketching precision [5, 48].

Planar input devices, such as touchscreen and graphic tablets, have also been used in many pen-based design systems in mixed and virtual reality for sketching [4, 13, 17] or model manipulation [12, 43, 46]. However, these devices may not be sufficient to support the variety of virtual objects in VR. While some of these design systems project a non-planar virtual surface onto a flat physical surface and offer passive haptic feedback of contact, critical model information pertaining to physics and geometry remains absent. There can be a discrepancy between the virtual and physical surfaces, which may impact the interaction performance and immersion. Additionally, the transfer of 2D sketches into 3D models can be technically challenging and learning-demanding [4, 6].

To enable direct sketching or writing on a virtual model, researchers have investigated using a physical object as a tangible proxy of a virtual object for users to draw on [40, 48]. The study found that the precise geometric information of tangible proxies can provide physical guidance and lead to a significantly lower line-based sketching deviation [48]. However, fabricating physical replicas of the diverse virtual objects can be expensive, time-consuming, and impractical [22, 23, 37, 42].

2.2 Dynamic Shape Displays

Dynamic shape displays have been extensively explored in VR to render various virtual objects and create tangible surfaces with different properties such as size, form, curvature, and texture [28, 28, 34]. Some shape displays utilize an array of actuated pins to render the shapes of virtual objects [18, 39]. While these displays can render high-fidelity 2.5D shapes of virtual objects, the size and weight of the pin actuation mechanism make them inadequate as hand-held devices. Other devices use more lightweight shape-rendering mechanisms, such as lower-resolution pin arrays [8, 54], a moving and tilting finger rest [8], and a volume-changing structure [20], so that the device can be held in the user's hand and used to explore virtual objects in 3D space. While these shape displays show great potential in facilitating user perception of virtual objects, including touching, tracing, and even breaking objects, they lack a sufficiently large and continuous surface for designers to interact with 3D models by sketching or writing on their surfaces.

Bendable shape displays use multiple flaps controlled by motors to render various surface shapes [21, 31, 37]. Different from the previous shape-changing devices, these displays produce a relatively continuous and larger surface that may be adequate as a drawing surface. However, current bendable shape displays predominantly focus on simulating objects that function as graspable tools to create a tangible and immersive experience in VR, rather than creating an interaction surface to support precise and high-performance interactions such as sketching. For example, they still have creases and gaps between flaps, which are not ideal for presenting surfaces. Although not automatically changing its shape, Morphaces [32] proposes to use a deformable physical surface for sketching on virtual surfaces.

While extensive research has been conducted on dynamic shape displays, little attention has been given to shape-changing sketching surfaces, which motivated our work.

3 DYNAMIC SHAPE DISPLAY FOR VR SKETCHING

To equip a dynamic shape display for enhanced sketching experience in VR, we considered the following design goals for the device: 1) have an interaction surface large enough for users to sketch on it; 2) is lightweight and graspable by the user for easy handling; 3) is able to detect light contacts of a pen to support smooth drawing; 4) can quickly and responsively render surfaces with various shapes. In this section, we discuss the hardware implementation of our shape display and sketching pen, and the interaction design of our system.

3.1 VRScroll

VRScroll is a dynamic shape display designed to help users precisely sketch in VR by changing its shape to mimic the surface of the virtual object (Figure 2). Bending-deformation techniques have been extensively explored to create dynamic surfaces [19, 30, 33, 35]. We chose a motor-driven bending mechanism [21, 31, 37] to execute the shape change due to its extendability, low cost, easy fabrication, and its ability to morph into various non-planar surfaces by flexing at edges at a high speed. VRScroll features 7 flaps that facilitate its shape deformation, utilizing six concentric-driven links to connect these flaps [53]. This design allows for a wide range of rotation between the flaps.

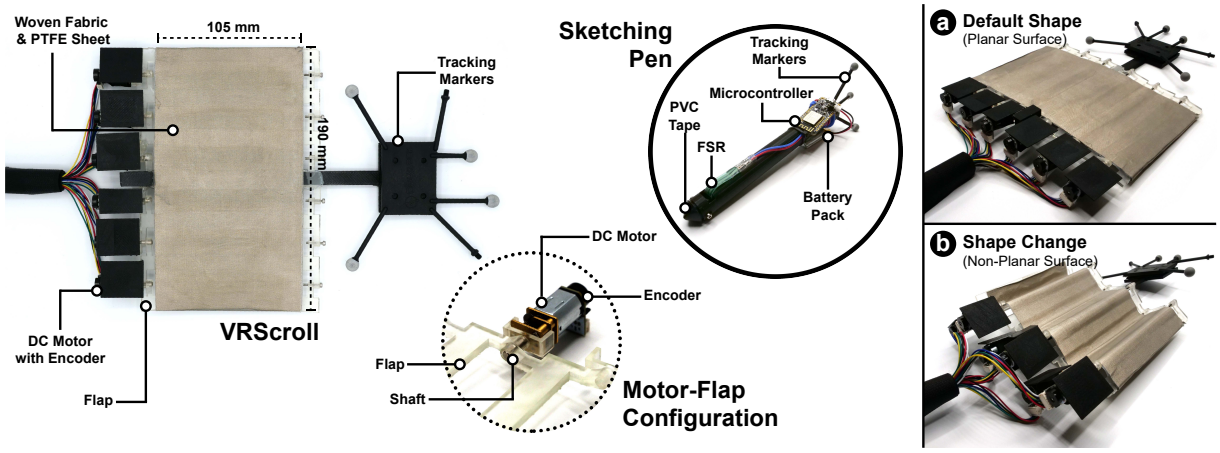


Figure 2: VRScroll device. Example surfaces rendered by VRScroll: (a) planar surface, (b) non-planar surface.

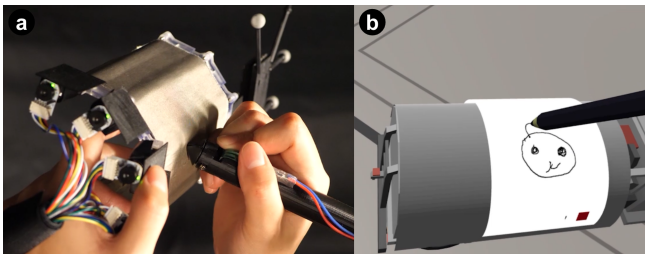


Figure 3: VRScroll Interaction. (a) VRScroll mimics the target shape. (b) Sketches are rendered on the virtual surface.

VRScroll has a dimension of $190mm \times 120mm \times 4mm$ and weighs 157 g, which is similar to a tablet. Each flap in VRScroll is fabricated with resin material using an SLA 3D printer, and each flap link is controlled using a DC motor with an encoder (Adafruit N20, 100 rpm, 1:100 gear ratio). We utilized 3 motor drivers (Adafruit TB6612) and implemented PID controls to drive the 6 motors, and two Arduino UNO WiFi REV 2 microcontrollers were used to control the entire system. All motor drivers and microcontrollers were powered by a 2S Li-Po battery (7.4V, 450mAh). Each flap supports a rotation range of ~280 degrees. All flaps can rotate simultaneously, with each flap rotating at a speed of ~180 ms/90 degrees. A $190mm \times 105mm$ flexible PTFE sheet and a woven fabric cover the flaps to create a continuous and smooth touchable surface.

The number of flaps on the device can be modified. However, we chose a 7-flap configuration to minimize the fabrication workload and construct a device that is comparatively lightweight, yet able to fulfill the size requirements of a sketching pad and offer a sufficient array of shapes for our designated sketching tasks.

Finally, reflective markers are attached to VRScroll which are used to track it in 3D space using the OptiTrack camera system.

3.2 Sketching Pen

We implemented a pen to create sketches on the VRScroll (Figure 2). The sketching pen has a cylindrical structure with a height of 170 mm and a radius of 8.5 mm, and weighs 47 g. We use a force-sensitive resistor (FSR) between the tip and the barrel of the pen to precisely detect the contact between the surface and the pen. Lastly, black PVC tape is wrapped around the pen tip to make it smoother. An Adafruit Feather HUZZAH ESP8266 board powered by a 3.7 V Li-Po battery (900mAh) is used to measure the force and send it to the PC running the sketch application using UDP via Wi-Fi. Similar to VRScroll, the sketching pen also has reflective markers attached to it for tracking.

3.3 Interaction Design

The interaction of VRScroll for sketching in VR involves three steps - *selection*, *transformation*, and *sketching*. Presented with multiple virtual objects, the user can move the VRScroll device close to the target one to select it. The shape transformation will then be triggered automatically, enabling VRScroll to mimic and align with the target surface (Figure 3a). Meanwhile, the target virtual surface is snapped to VRScroll, allowing the user to start sketching on the surface using the physical VRScroll. Finally, the user can use the pen to create *sketches* on the physical VRScroll, which are simultaneously rendered on the texture of the virtual surface (Figure 3b).

4 SKETCHING STUDY

We conducted a user study to investigate the effect of having a shape-changing physical surface (VRScroll) on the sketching performance in VR. We used mid-air sketching (without a physical surface) as a baseline for comparison, which aimed to mimic the standard pen-based sketching methods in current commercial VR systems [2]. This study involved participants tracing simple trajectories and freely sketching using a pen, both with and without VRScroll. For clarity, we will refer to the condition with VRScroll device as *VRScroll*, and the condition without the device, where participants solely relied on visual feedback, as *InAir*. To understand the effect of different surfaces on the sketching performance, we tested five sketching surfaces that vary in the form of bend (planar, curved, and angled) and the direction of bend (concave and convex), as shown in Figure 5.

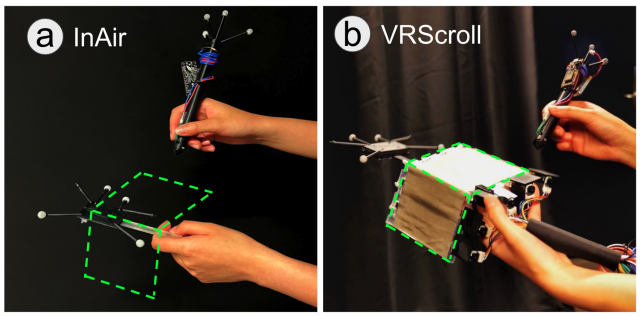


Figure 4: User study setup. Two interaction methods were compared: (a) InAir. (b) VRScroll. The green dash line represents the virtual surface presented in VR.

According to previous research that demonstrated the advantages of using grounded planar surfaces in VR to enhance sketching performance [5], reduce completion time, and decrease physical exertion compared to in-air interaction [48], we investigated whether VRScroll, which equipped with a portable shape-changing surface, would offer similar benefits on non-planar virtual surfaces. Based on the characteristics of the two interaction methods, this study sought to test the following hypotheses:

(1) With the physical surface (VRScroll), users will produce more precise sketches with clearer strokes than only relying on visual feedback (InAir).
(2) With the physical surface (VRScroll), users will complete the tracing and sketching tasks faster and with less workload than only relying on visual feedback (InAir).
(3) The differences in precision and speed during tracing and sketching between using the physical surface (VRScroll) and relying on visual feedback (InAir) will be greater on non-planar surfaces than on planar surfaces.

4.1 Apparatus

The study software was developed using Unity and ran on a laptop with an Intel Core i7 processor and NVIDIA RTX 3080 GPU. Participants wore a Meta Quest 2 VR headset and used a 6-DOF pen with their dominant hand. The headset and handheld devices were tracked by OptiTrack trackers at a 360 Hz sampling rate, and the mean error of OptiTrack tracking was 0.28 mm.

4.2 Method

4.2.1 InAir Interaction. For the *InAir* condition, participants held a 20 g sidebar in their non-dominant hand as shown in Figure 4a. The sidebar was a narrow, rectangular acrylic piece that represented the leftmost edge of the virtual drawing surface, which had a 4-mm thickness. The movement of the sidebar directly controlled the position and orientation of the virtual surface. Participants held the pen using their dominant hand to perform the tracing and sketching tasks. Since there was no physical surface, pen contact with the virtual surface was determined by checking the collision between the pen tip and the virtual surface. The visual feedback allowed the pen to penetrate the surface, enabling users to accurately determine the position of the pen tip.

4.2.2 VRScroll Interaction. For the *VRScroll* condition, participants held the VRScroll device in their non-dominant hand by grasping its body as shown in Figure 4b. Same as *InAir*, VRScroll also situated a 4 mm thick virtual surface in VR. The contact of the pen was determined by checking the force measured at the pen tip.

4.3 Tasks

Tracing curves and straight lines has been tested in many previous studies on touch interaction in mixed and virtual reality [8, 48, 52]. We used two tracing tasks; one was to trace a circle with a 35 mm radius and the other was to trace a $70mm \times 70mm$ triangle. Both trajectories were displayed on the center of the virtual surface as shown in Figure 5. We also used one freestyle sketching task because it is a more advanced task [5, 24], with more intricate strokes [47].

4.4 Participants

Twelve individuals (6 males, 6 females, 19-32 years old with a mean age of 22.67) participated in the study. All participants were right-handed. Four participants were familiar with VR devices through VR games, and eight participants had tried VR headsets before. One participant had 3D design experience with AutoCAD. Another participant who worked on urban landscape design had the experience of sketching using VR devices. The participants were paid USD 20 for their participation. The study protocol was approved by the University of Virginia institutional review board.

4.5 Study Design

The tracing task was designed as a $2 \times 2 \times 5$ within-subject study, with three independent variables *Method* {InAir, VRScroll}, *Trajectory* {triangle, circle}, and *Surface* {planar, convex angled, concave angled, convex curved, concave curved} as shown in Figure 5. The presentation of Method and Trajectory was counterbalanced using a balanced Latin square design, and the Surface order was randomized. With each Method, participants traced triangles 5 times and circles 5 times on each surface. During the tracing, each participant performed a total of 100 trials (i.e., $2(Method) \times 5(Surface) \times (2 \times 5(Trajectory)) = 100\, trials$).

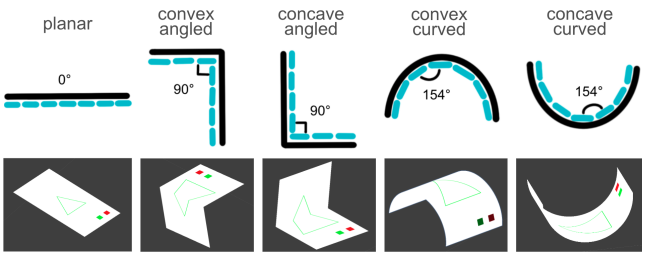


Figure 5: Five surfaces used for the sketching study. The virtual surfaces rendered in VR are depicted in black. The physical surfaces created by VRScroll are highlighted in blue line segments, each segment represents one flap. Green lines show the trajectories used in the tracing task.

The freestyle sketching task was designed as a 2×5 within-subject study, with two independent variables *Method* {InAir, VRScroll}

and *Surface* {planar, convex angled, concave angled, convex curved, concave curved}. The presentation of the Method was counterbalanced, and the Surface order was randomized. With each Method, participants drew one free sketch on each surface. During the free sketching task, each participant performed a total of 10 trials (i.e., 2 (Method) x 5 (Surface) x 1 (Sketch) = 10 trials).

To avoid confounding and distraction, only the virtual surface and pen were presented to participants in the study. During the tracing task, we instructed participants to follow the given trajectories in one direction, either clockwise or anti-clockwise, as precisely and quickly as possible. For the freestyle sketching task, we did not specify the content given participants might have different levels of sketching capabilities. Participants could sketch whatever they wanted, but each participant should sketch the same content in their sketches across all conditions. In addition, participants were encouraged to sketch more details, such as shapes and textures, in the freestyle sketching task. During the task, participants were allowed to move the surface and pen in a way that they felt comfortable and effective.

In general, each participant finished 110 trials in this study, which lasted between 60-75 minutes.

4.6 Measures

During the experiment, a log file recorded the time, 3D positions of the pen, VRScroll, virtual surface, and contact between the pen and surface at a rate of 70 Hz. The contact point was calculated by mapping the 3D position of the right index fingertip onto the virtual surface. The mapping direction is the line of sight direction from the eye to the operating finger. Both tracing and sketching results were derived from the 2D texture of the virtual surface as shown in Figure 3b. For the collected data, we used different metrics to evaluate the tracing, sketching performance, and user behavior.

4.6.1 Tracing Task Performance. To evaluate the quality of tracings, we analyzed the tracing-trajectory precision, stroke smoothness, number of strokes, task completion time, and user behavior.

Tracing Precision. To evaluate the precision of triangle- and circle-tracing, we first resampled each tracing trajectory to 100 equidistant points (px, py) on the 2D coordinate, with the center located at (0,0). The tracing precision was then calculated through the offset between the participant-drawn trajectory and the target by the Mean Projection Deviation (MPD) [5]. A smaller offset (MPD) indicates that the stroke drawn by the participant had higher precision and was more consistent with the target trajectory.

Triangles were first segmented into three straight lines (i.e., the three edges) and then transformed to be parallel to the x-axis with the line center located at (0,0). After the processing, MPD is the average distance between the points and the target line, which is the deviation from the x-axis. As shown in Formula 1, $MPD_{triangle}$ takes n as the number of points on the stroke, py_i are the corresponding values of the i^{th} point on the y axes.

$$MPD_{triangle} = \frac{1}{n}\sum_{i=1}^{n}(py_i) \tag{1}$$

For circle tracing, MPD is the average distance between the points and the target circle. As shown in Formula 2, MPD_{circle} takes n as the number of points on the stroke, px_i and py_i are the corresponding values of the i^{th} point on the x and y axes, and r is the radius of the target circle.

$$MPD_{circle} = \frac{1}{n}\sum_{i=1}^{n}(\sqrt{(px_i)^2 + (py_i)^2} - r) \tag{2}$$

Stroke smoothness. For the tracing task, we computed Mean Fairness Deviation (MFD) [5] to evaluate the smoothness of the strokes. MFD was defined as the mean curvature difference between adjacent points. Smoother strokes have a smaller MFD. Since the participants may complete trials using multiple strokes, we calculated MFD for each stroke in a trial and averaged them.

As shown in Formula 3, n is the number of points on the stroke, and C_i is the curvature of the i^{th} point on the stroke.

$$MFD = \frac{1}{n-1}\sum_{i=1}^{n-1}\frac{|C_i - C_{i+1}|}{avg\,(C_i, C_{i+1})} \tag{3}$$

Task Completion Time. Task completion time was recorded from the time participants started drawing the first stroke to the time they finished the last stroke. A shorter task completion time might demonstrate that the participant traced or sketched at a higher speed.

Number of Strokes. To understand participants' tracing behavior, we also calculated the number of strokes that participants drew to complete a tracing or free sketching. Each stroke was recorded as the pen was lifted from the surface, which might provide insights into how often participants controlled the surface and repositioned the pen.

User Behavior. Since the tracing task had controlled targets and involved continuous hand movement, total hand movement and total surface movement were also assessed during the tracing task to understand the involvement and coordination of the dominant and non-dominant hands.

4.6.2 Sketching Task Performance. We designed a free sketching task to evaluate the quality of complex sketches produced with and without VRScroll. To subjectively evaluate the quality of drawings, we recruited 30 reviewers from Amazon Mechanical Turk (MTurk) to rate the clarity of participants using a 10-point rating scale (1 being least clear and 10 being most clear). The MTurk workers received USD 3 for their effort.

4.7 Workload and Usability

We used the NASA Task Load Index [11] to measure the workload for each method, and the participants were asked to complete the self-assessment form after each method. We also designed a custom questionnaire to rate both the system's usability and participants' experience by incorporating questions from the System Usability Scale [9] along with additional experience-related questions. The questionnaire consisted of the following questions to be answered using a 5-point Likert Scale (1: strongly disagree and 5: strongly agree): if sketching using *Method* 1) feels realistic, 2) feels intuitive, 3) makes using pen easy, 4) is controllable, 5) is comfortable, and 6) feels confident. The participants were also asked to choose the

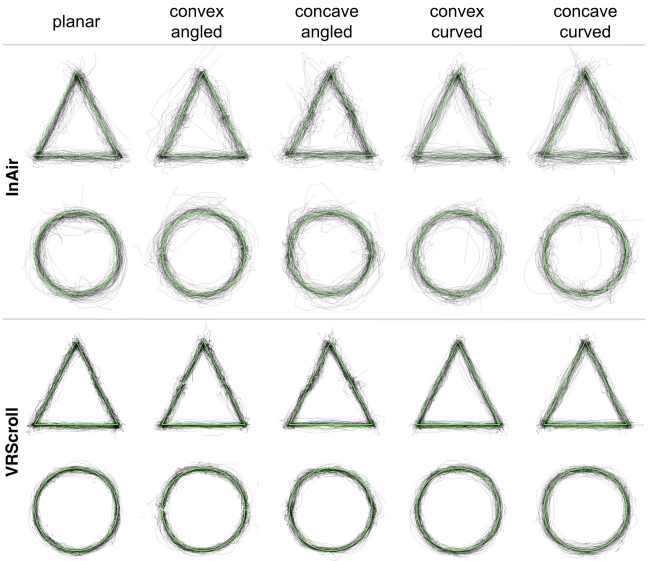


Figure 6: The tracing strokes drawn by all participants are depicted in black. The target shapes are highlighted in green.

method they preferred and to provide feedback about their experience of using the methods. The questionnaire was given after completing all tasks.

4.8 Data Analysis

For parametric measurements, all data were tested for normality and applied Aligned Rank Transform (ART) [50] for non-normally distributed factors. Repeated-measure ANOVA tests were used to analyze the normally distributed data with $p = 0.05$ as the level of significance. If further post-hoc testing was necessary, pairwise t-tests with Bonferroni correction were conducted. For the non-normally distributed data, ART ANOVA tests were adopted and the ART-C [14] procedure was used for pairwise post-hoc comparisons when necessary. For the non-parametric measures (subjective ratings), a Friedman's ANOVA test was performed on the Likert results. Mann-Whitney post-hoc tests with a Bonferroni correction were conducted if needed.

5 RESULTS

The user study evaluated participants' performance of tracing and sketching tasks with and without VRScroll on various surfaces. Here we present the measurements and outcomes for the two tasks.

5.1 Tracing

Overall, tracings created with VRScroll show fewer abnormal strokes and are better aligned with the target shape (See Figure 6). The effects of VRScroll and the five surfaces on different metrics are shown and described in turn.

5.1.1 Tracing Precision. *Method* had a significant effect on the tracing precision ($F_{(1,11)} = 21.1$, $p < 0.001$). As shown in Figure 7b, tracing shapes with *VRScroll* ($M = 1.22mm, SD = 0.45mm$) led to a significant 40.49% increase in precision compared to the *InAir*

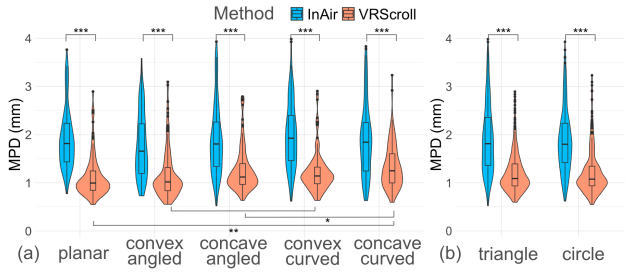


Figure 7: (a) MPD of the tracing trajectory on various surfaces. (b) MPD of tracing a triangle and a circle. Lower MPD indicates more precise tracing.

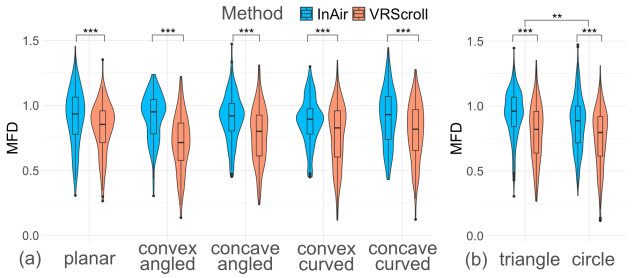


Figure 8: (a) MFD of the tracing trajectory on various surfaces. (b) MFD of tracing a triangle and a circle. Lower MFD indicates more smooth strokes.

tracing ($M = 2.05mm, SD = 1.00mm$). While *VRScroll* improved the trajectory precision as shown in Figure 7a, interaction analysis found it showing relatively less benefit on concave surfaces (angled: $M = 1.26mm, SD = 0.45mm$, curved: $M = 1.33mm, SD = 0.45mm$) compared to convex (angled: $M = 1.17mm, SD = 0.51mm$, curved: $M = 1.22mm, SD = 0.42mm$) and planar surfaces ($M = 1.11mm, SD = 0.42mm$). In addition, *Surface* did not make any significant differences under the *InAir* condition ($p > 0.5$).

5.1.2 Stroke Smoothness. Statistical analysis revealed that both *Method* ($F_{(1,11)} = 16.2$, $p < 0.001$) and *Trajectory* ($F_{(1,11)} = 30.2$, $p < 0.001$) resulted in significant differences in stroke smoothness. The interaction between them was also found to be significant ($F_{(1,11)} = 15.5$, $p < 0.001$). As shown in Figure 8b, *VRScroll* improved stroke smoothness (smaller MFD) for triangle tracing ($M = 0.76, SD = 0.21$) compared to *InAir* ($M = 0.94, SD = 0.19$). For circle tracing, *VRScroll* also produced smoother strokes ($M = 0.75, SD = 0.22$) than *InAir* ($M = 0.85, SD = 0.21$). In addition, the benefits of *VRScroll* were more pronounced for circle tracing ($p < 0.001$). However, there was no significant difference found among surfaces ($p > 0.5$, see Figure 8a).

5.1.3 Task Completion Time. *Method* ($F_{(1,11)} = 30.6$, $p < 0.001$), *Surface* ($F_{(4,44)} = 29.4$, $p < 0.001$), and *Trajectory* ($F_{(1,11)} = 11.4$, $p < 0.01$) had significant effect on tracing completion time. As shown in Figure 9b, participants spent $11.10s (SD = 4.95s)$ to trace a circle with *VRScroll* while they only spent $7.96s (SD = 4.24s)$ under *InAir* condition. Similarly, tracing a triangle with *VRScroll* ($M =$

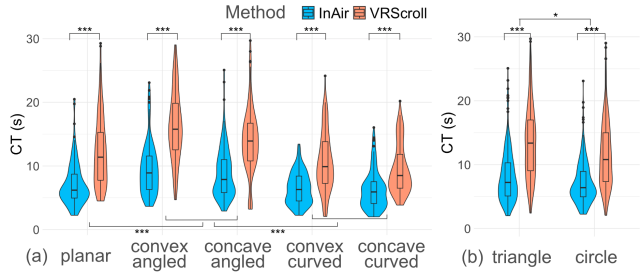


Figure 9: (a) The task completion time (CT) of tracing on various surfaces. (b) CT of tracing a triangle and a circle.

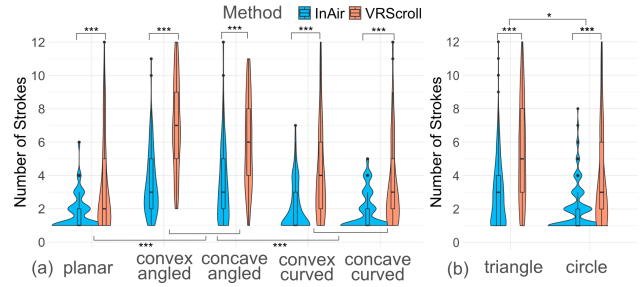


Figure 10: (a) The number of strokes that participants drew for tracing on various surfaces. (b) The number of strokes for tracing a triangle and a circle.

14.7s, $SD = 7.08s$) took almost twice as long as *InAir* tracing ($M = 7.37s$, $SD = 2.97s$). In addition, as shown in Figure 9a, participants spent significantly more time when drawing trajectories on angled surfaces (convex: $M = 13.8s$, $SD = 7.51s$, concave: $M = 11.5s$, $SD = 5.28s$) than planar surfaces ($M = 9.85s$, $SD = 5.58s$), followed by curved surfaces (convex: $M = 8.53s$, $SD = 4.21s$, concave: $M = 7.85s$, $SD = 3.79s$).

5.1.4 Number of Strokes. The number of strokes was significantly affected by *Method* ($F_{(1,11)} = 31.5$, $p < 0.001$), *Surface* ($F_{(4,44)} = 21.4$, $p < 0.001$), and *Trajectory* ($F_{(1,11)} = 26.2$, $p < 0.001$). As shown in Figure 10b, when tracing a triangle, participants drew more strokes with *VRScroll* ($M = 6.11, SD = 5.56$) than *InAir* ($M = 2.43, SD = 1.68$). Participants also drew more strokes when tracing a circle with *VRScroll* ($M = 5.85, SD = 4.90$) than *InAir* ($M = 2.56, SD = 2.06$). Additionally, angled surfaces resulted in the largest number of strokes (convex: $M = 6.85, SD = 5.84$, concave: $M = 5.21, SD = 3.71$), followed by curved surfaces (convex: $M = 3.80, SD = 4.39$, concave: $M = 2.64, SD = 2.15$) and planar surfaces ($M = 2.70, SD = 2.87$) as shown in Figure 10a.

5.1.5 User Behavior. The total travel distances of the pen ($F_{(1,11)} = 30.8$, $p < 0.001$) and the surface ($F_{(1,11)} = 23.3$, $p < 0.001$) in a tracing trial were significantly larger in *VRScroll* than *InAir* conditions. With *VRScroll*, the average total pen movement for a trajectory-tracing was $0.37(SD = 0.30)$ m and the total surface movement was $0.10(SD = 0.10)$ m, while the pen and surface movements in *InAir* was $0.32(SD = 0.20)$ m and $0.09(SD = 0.09)$ m, correspondingly.

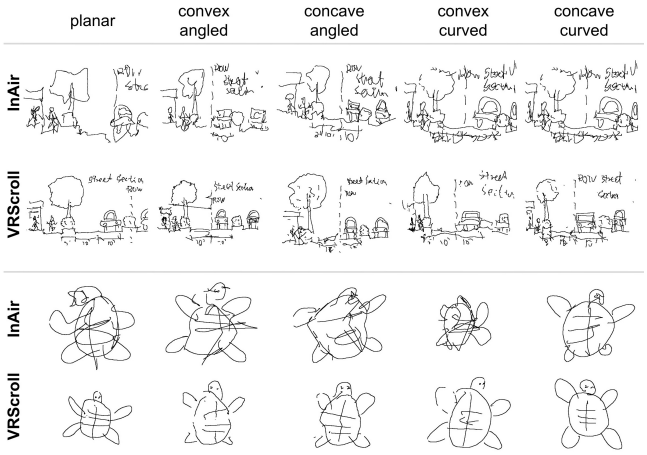


Figure 11: The collection of sketches drawn by two participants on different surfaces with and without VRScroll.

Surface also had a significant effect on pen ($F_{(4,44)} = 26.6$, $p < 0.001$) and surface movements ($F_{(4,44)} = 32.3$, $p < 0.001$). Drawing a trajectory on angled (convex: $M = 0.52m, SD = 0.36m$, concave: $M = 0.41m, SD = 0.25m$) surfaces resulted in more pen movement, while the pen traveled less on both planar ($M = 0.28m, SD = 0.17m$) and curved (convex: $M = 0.26m, SD = 0.16m$, concave: $M = 0.27m, SD = 0.19m$) surfaces. During each trajectory-tracing, angled (convex: $M = 0.17m, SD = 0.12m$, concave: $M = 0.10m, SD = 0.10m$) surfaces were moved most, followed by curved (convex: $M = 0.09m, SD = 0.08m$, concave: $M = 0.06m, SD = 0.07m$) surfaces and planar ($M = 0.05m, SD = 0.05m$) surfaces.

5.1.6 Correlations Between Measures. We found that tracing precision (MPD) and stroke smoothness (MFD) have a weak negative correlation with the number of strokes (Pearson's $r = -0.26$, $p < 0.001$) and a moderate negative correlation with task completion time ($r = -0.44$, $p < 0.001$). Higher precision and smoothness might result in more strokes, and take more time to draw a trajectory. Meanwhile, drawing more number of strokes led to longer task completion time, which was strongly and positively correlated ($r = 0.69$, $p < 0.001$).

5.2 Freestyle Sketching

Figure 11 shows drawings from two participants as examples. Overall, the drawings made with VRScroll looked better than InAir, with more coherent lines and detailed textures, while the sketch quality varied among participants. It was also interesting to see that participants tend to make smaller sketches with more details with VRScroll, which may indicate better support for high-resolution sketching.

Figure 12 shows the sketch clarity ratings made by MTurk workers. Analysis revealed a significant effect of *Method* ($F_{(1,11)} = 21.1$, $p < 0.001$) on the rating for stroke clarity. Using *VRScroll* ($M = 5.91, SD = 2.33$), participants created more clear sketches than sketches drawn under *InAir* condition ($M = 4.93, SD = 2.43$). While the shape of surfaces did not impact sketching performance when performed in the air ($p > 0.5$), it exhibited a significant effect when

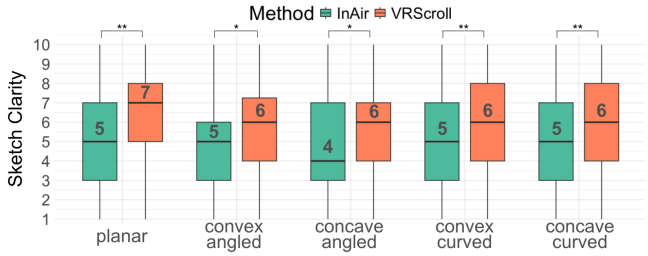


Figure 12: The clarity rating of the sketches. Median values are shown.

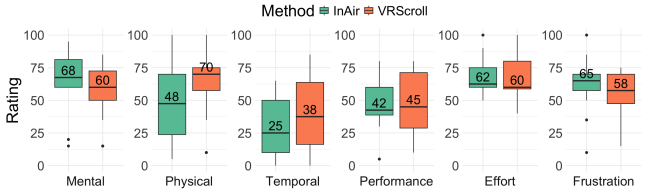


Figure 13: Mean workload for completing tasks with and without VRScroll. Median values are shown.

sketching was done using *VRScroll* ($F_{(4,44)} = 7.41$, $p < 0.001$). Post-hoc tests showed that the planar surface ($M = 6.38, SD = 2.34$) enabled the best stroke clarity, followed by curved surfaces (concave $M = 6.02, SD = 2.32$, convex: $M = 5.86, SD = 2.30$) and angled surfaces (convex: $M = 5.89, SD = 2.31$, concave: $M = 5.60, SD = 2.29$).

5.3 Workload, Usability, and Experience

Figure 13 and Figure 14 show the workload and usability ratings. While no significant difference was found in workload ($F_{(1,11)} = 0.03$, $p > 0.5$), *VRScroll* was rated as significantly more realistic ($F_{(1,11)} = 19.5$, $p < 0.001$), intuitive ($F_{(1,11)} = 5.82$, $p < 0.05$), controllable ($F_{(1,11)} = 4.33$, $p < 0.05$) than *InAir*. Participants also felt more comfortable ($F_{(1,11)} = 4.50$, $p < 0.05$) and confident ($F_{(1,11)} = 4.56$, $p < 0.05$) when interacting with *VRScroll*.

As for method preference, 8 participants (66.7%) responded that they prefer *VRScroll* over *InAir*. The mostly-mentioned reason for the preference towards *VRScroll* was the increased precision (5/8, e.g. "much more effective and the shape is much better" (P4)). Another popular reason was the feeling of contact with the physical surface provided (4/8, e.g., "can feel your sketch" (P6), "I like pressing no the surface" (P12)). Among the four participants who preferred not using *VRScroll*, two of them mentioned the difficulty of freely moving the pen, which may interfere with the physical shape and become more noticeable when drawing on concave surfaces. We also observed that when participants held the pen at a tilted angle or moved it dramatically, the pen body often hit the physical surface. Other reasons for the preference towards *InAir* are the uneven surface of the device affecting the drawing and the extra effort for holding the device, each mentioned by one participant.

When asked about the sketch experience with *VRScroll*, 7 participants (58.3%) mentioned that the sketching felt realistic (e.g., "has a real 'paper' to sketch on" (P4), "It feels very realistic"(P1)).

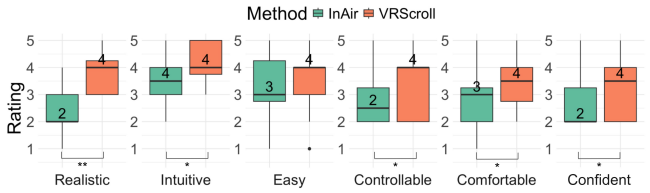


Figure 14: Average ratings for the usability and experience questions. Median values are shown.

Two participants appreciated that they could control the pen and surface easier with *VRScroll* (e.g., "I feel more bonded by the surface." (P11)). However, three participants mentioned the uneven surface (e.g., "harder to draw straight lines because of the ribs in the surface" (P11)). Regarding the experience under *InAir* condition, six participants reported difficulties in controlling the pen and surface (e.g., "it's hard to locate the pen"(P6), "can't control the sketch"(P5)), four participants (33.3%) mentioned that sketching was unstable (e.g., "It might require more stable hands and control to perform good"(P1)) and three participants (25.0%) mentioned the lack of tactile feeling (e.g., "I can't feel anything, frankly, it is not a good experience"(P7)). Aligned with participants' feedback about system controllability, we found that participants moved the pen less with VRScroll, while they tended to exaggerate pen movements in the InAir condition to ensure the pen either lifted from or collided with the virtual surface.

6 DISCUSSION

6.1 Effect of VRScroll on Sketching in VR

The results of our study showed several benefits of having VRScroll for drawing in VR. For simple tracing tasks, there were significant improvements in tracing precision and stroke smoothness when VRScroll was used compared to in-air tracing. The freestyle sketches created using VRScroll were also rated as clearer by external evaluators. These improvements in sketch precision confirm our first hypothesis and are consistent with earlier studies that have shown the benefit of utilizing a grounded physical surface for VR sketching [5] and sketching around a 3D-printed physical object [48]. In addition to the sketch quality, participants also found the sketching experience using VRScroll more realistic, intuitive, and controllable. They felt more comfortable and confident when using VRScroll.

However, having the physical surface did not make sketching faster, which is contradictory to our second hypothesis. Completing the tracing tasks without using VRScroll was faster, and the participants used fewer strokes. There can be several possible reasons. First, the InAir condition only provided visual feedback that needs less cognitive attention and time to process [8]. However, the added physicality of the surface might have encouraged the participants to be more precise and careful, leading to slower completion times and more strokes. Second, the physical constraints of the surface might have affected the speed of pen movement. Given that there was no comment about the physical surface slowing down the movement, we conjecture that the former can be the reason.

In both VRScroll and InAir conditions, surface shape had a significant effect on completion time and it took longer for participants to complete tracing tasks on angled surfaces than other surfaces, and on flat surfaces than curved surfaces. However, the effect of surface shape was more pronounced for VRScroll than InAir. For InAir condition, there was no significantly different effect of surface shape on the quality of sketches, i.e., MPD and sketch clarity. On the other hand, when using VRScroll, MPD was significantly worse for concave surfaces than others, and sketch clarity was significantly better when drawn on a flat surface. These results demonstrate that the different surface features significantly affect task performance. However, they fail to fully support our third hypothesis, as VRScroll did not exhibit advantages on concave surfaces. In fact, this study revealed a potential limitation of utilizing a non-planar physical surface to represent the virtual surface. Specifically, the replicated physical surface may restrict the interaction space and limit pen movements, which may not happen if not using a physical surface.

6.2 Design Implications

Given the performance benefits and improved experience of VR sketching with VRScroll, we believe that it is worth adopting a shape-changing device for tasks requiring precise interactions. While the device used in our study has its drawbacks, such as the relatively low shape-rendering resolution (7 flaps) and 1-dimensional shape change, more capable shape-changing devices can be developed in the future. Here, we share our insights on the design of sketching interactions using shape-changing devices derived from the study.

First, it is important to understand that physicalizing the virtual surface can create challenges caused by the laws of physics, which do not exist in the virtual world. In our study, concave surfaces had significantly worse tracing precision than other shapes and were slower than their convex counterparts. The participants' comments about the interference between the pen and the surface while drawing on concave surfaces align with these findings. In virtual drawing scenarios, the size of a controller or a pen does not matter, even when drawing in a tight and confined area. However, if the virtual object is physicalized using a shape display, the physical limitations can also be inherited. Instead of always rendering the physical features of the virtual object, allowing users to choose areas to be physically rendered, or developing an algorithm to predict potential physical interference and avoid rendering of such areas may help maximize the utility of the physical interaction surface.

Second, not all interactions need to be done on the physical surface. While our study showed improvements in drawing quality with the physical surface, real-world drawing will involve various types of interactions with different levels of complexity, such as tools, switching modes, and tools and controlling parameters. Interactions that do not need precision may be completed using mid-air interactions, while precise tasks such as sketching and annotating can be done on the physical surface.

Third, the shape features may be used as physical guides. Earlier, we discussed the potential limitations created by the rendered physical features. However, such constraining physical features can be intentionally created to physically guide the movement of the pen, as used in the physical proxy study [48]. For example, in VRScroll, two adjacent flaps can be elevated to create a linear physical path that guides the pen and improves sketch precision, or form a boundary that restricts pen movement.

6.3 Limitations and Future Work

Our work has highlighted using a shape-changing device to replicate a range of virtual surfaces, facilitating accurate sketching and improving the drawing experience on different surfaces. To avoid confounding, this study used a highly controlled setup, where the shape of VRScroll was limited to planar, angled, and curved surfaces. The results of this study may not translate to real use, and future work should investigate the performance and experience of using the shape-changing device for tasks in more realistic scenarios. This will require further development of interaction techniques and algorithms for aligning physical and virtual surfaces.

This study only investigated a limited set of surface shapes along one axis due to the shape-rendering limitation of VRScroll. Further study will be needed to understand the effects of using a physical surface for more complex shapes. This can be done after implementing a higher-fidelity shape display using more advanced shape-changing mechanisms such as using multiple shape-memory polymers [51], self-reconfiguring modular robots [10, 38, 55], or an array of linear actuators and flexible surfaces [16, 41]. Another potential direction is to employ visuo-haptic illusion techniques [7] to approximate virtual shapes and dynamically change the visualization of a surface shape and pen's movement to make users feel the surface varying its shape in multiple dimensions. While the current study successfully demonstrated the effects of having a physical surface, a larger-scale study with a more diverse participant pool will be needed for an in-depth understanding of various factors.

Finally, while the technologies and techniques for physically rendering shapes are advancing, achieving the level of fidelity and resolution in dynamic shape displays that match visual displays remains extremely challenging. For the foreseeable future, the shape-changing device may only be able to approximately mimic the shape of virtual objects. However, we believe that this limitation does not negate the potential benefits of providing a shape-changing interaction surface. Instead, it can be crucial to investigate the minimum fidelity and resolution requirements to effectively support precise and natural on-surface interactions.

7 CONCLUSION

This paper proposed using a dynamic shape display to support precise sketching on virtual objects in VR. We developed VRScroll, a scroll-like shape-changing device designed to support on-surface pen interaction. Through a comparative user study, we investigated the effects of having a physical surface created using VRScroll on sketching performance. The study revealed that utilizing VRScroll could significantly improve the quality of sketches and provide a more realistic and intuitive experience. Based on our findings, we presented several design implications for equipping dynamic shape displays to facilitate precise sketching in VR. We hope our work will inspire future investigations into shape-changing interfaces, which may move beyond immersive shape manipulation and toward supporting more inventive and productive interactions in VR.

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