PhoneCanvas: 3D Sketching System Using a Depth Camera-Equipped Smartphone as a Canvas

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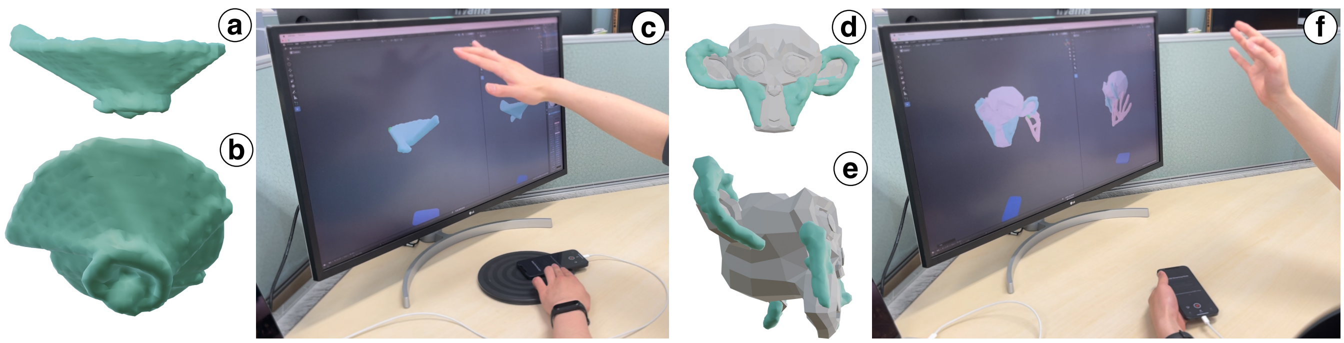

Figure 1: Examples of situations where PhoneCanvas is used and its design space. (a) Side view and (b) oblique view of a plate. (c) Sketching of a plate. (d) Front view and (e) side view of the modified Blender Suzanne model. (f) Modification of Blender Suzanne.

ABSTRACT

We present PhoneCanvas, a system using a depth camera-equipped smartphone as a canvas, which enables users to draw 3D sketches and view their sketches on a PC in real-time. Users can draw lines, erase lines, and draw surfaces by varying their hand gestures and rotating 3D models by rotating their smartphones. This system allows for 3D sketching operations using hand gestures, with the aim of providing operations for 3D modeling beginners to perform rapid prototyping. PhoneCanvas addresses the issue of a few 3D sketching systems for beginners balancing both installation costs and operability. We conducted studies with 3D modeling beginners to test the performance of the system. The study results showed that the system can be used for rapidly prototyping various 3D models and discussions.

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CCS CONCEPTS

• **Human-centered computing** → *Graphics input devices.*

KEYWORDS

3D modeling, mid-air drawing, freehand drawing, mid-air interaction, 3D concept design, rapid prototyping

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1 INTRODUCTION

Professional 3D modeling software on PCs, such as Blender [16], Maya [3], and ZBrush [40], offer tools that make modeling enjoyable and efficient for intermediate to expert 3D artists. However, mastering such software requires considerable effort and time [31]. In addition, applications that realize 3D modeling in virtual reality (VR) are attracting attention; more and more users are adopting commercial VR modeling tools (e.g., Tilt Brush, Quill, Gravity Sketch, and A-Painter) to sketch in mid-air freely and intuitively [29]. While modeling in a 3D environment is very intuitive, these tools rely on head-mounted displays (HMDs), leading to high installation costs.

In particular, if multiple people need to share 3D models in a meeting, each person requires their own HMD, further increasing the costs. Alternatively, there are 3D sketching systems in augmented reality (AR) that do not use HMDs and rely solely on mobile devices (i.e., smartphones and tablet computers) [18, 34, 54]. However, these systems have narrow operation areas because of a limited, small 2D display [34, 44] and the need to grasp a mobile device with one hand, which results in low operability. Thus, there is a trade-off between installation costs and operability. Few 3D sketching systems for beginners balance both installation costs and operability.

In this paper, we present *PhoneCanvas* (Figure 1), a system using a depth camera-equipped smartphone as a canvas, which enables users to draw 3D sketches and view their sketches on a PC in real-time. This system allows for 3D sketching operations using hand gestures, with the aim of providing operations for 3D modeling beginners to perform rapid prototyping. The system anchors the 3D model to the smartphone, allowing users to rotate the model freely by rotating the smartphone. This rotation operation can improve users' depth perceptions in mid-air 3D sketching by introducing tangibility into the system. Furthermore, 3D sketching with rotation allows for the easy modeling of regular circular shapes, such as plates and disks. The system also enables collaborative work through real-time simultaneous modifications, annotations on existing objects, and rapid prototyping. This means that not only can beginners perform 3D sketching, but the system also enables collaborative tasks, such as brainstorming and rapid prototyping of 3D shapes among multiple users, including beginners, which is expected to support the generation of new ideas. The above functions are implemented with the rich hardware resources of a smartphone, contributing to the low installation costs of the system. In addition, the system complements 3D modeling operations on the PC by allowing users to quickly switch between traditional input devices, such as a mouse and a trackpad.

We first implemented a system with basic functionality. Then, in the initial exploration (Study 1), we identified areas for improvement and conducted system refinements. In the in-depth evaluation (Study 2), we investigated how quickly 3D modeling beginners could perform rapid prototyping of a 3D model using the improved system and whether it was possible for multiple users to discuss 3D shapes among themselves.

2 RELATED WORK

In the following, we discuss 3D modeling using HMDs and mobile devices, smartphone-based 3D controls, and hand-based creative interactions.

2.1 3D Modeling Using HMDs

Research on sketch-based modeling can be traced back to the mid-1980s [31]. Since the publication of the Canny Edge Detection algorithm [9], significant advancements have been made in sketch-based modeling [26, 29, 36, 39, 51]. Recently, there has been an increase in the number of users who are utilizing commercially available VR sketching tools, such as Tilt Brush [20] and Gravity Sketch [45], to sketch intuitively and freely in mid-air [29].

Interaction methods that improve the usability of 3D sketching in both VR and PC environments have been proposed [13, 29]. Research has also focused on supporting users' sketching skills in VR. Specific studies include snapping and a visual guide to improve accuracy [38, 39, 56], scaffolding to draw precise and aesthetic strokes [58], and sketching on physical objects [51]. Methods inspired by actual creative activities include a quick sketching method using the rotation of the sketch without an HMD [27] and an interactive canvas that includes rotation with an HMD [48].

3D modeling using HMDs has the advantage of allowing intuitive and immersive visualization and manipulation of 3D models. However, there are also some drawbacks, such as the high installation costs, the need for users to wear the device, and the time-consuming setup. There are time-consuming setup processes that involve scanning the surrounding environment to define the area of movement and making fine adjustments to eye comfort settings.

2.2 3D Modeling Using Smartphones

Compared with 3D sketching of VR environments using HMDs, 3D sketching of AR environments using mobile devices [6, 18, 34, 54] has lower installation costs and does not require wearing an HMD, resulting in shorter setup times. However, 3D sketching in AR on a mobile device is limited by the small 2D display, which restricts the operation area [34, 44]. Research has been conducted on the use of wearable peripheral displays to expand the limited field of view and enable the perception of surrounding objects. Examples include augmenting AR content with wearable external displays [44] and smartwatch screens [10, 15, 46]. Wells et al. [53] investigated device configurations and sizes suitable for AR collaborative work in the same location. The results show that the participants generally felt that they performed better when they shared a device or had access to a larger device screen. Furthermore, there are 3D modeling methods that use pen, touch, and air gestures on mobile devices [11, 41]. In contrast to the above work, our system uses the smartphone as the canvas, and the 3D sketch can be viewed on an external display. This approach extends the operation area compared to 3D sketches in the AR space of a single mobile device and facilitates the sharing of content.

2.3 Smartphone-based 3D Controls

Additional devices, such as tablets and pens, have been used to aid 3D modeling on PCs [2, 4, 5, 13, 17, 22, 25, 35, 37, 47]. However, these additional devices increase installation costs. Thus, research has been conducted on 3D interactions using smartphones, which are used daily. HandyCast [30], HoloTouch [12], and Tiltcasting [42] have been proposed for 3D operation in VR and AR. Büschel et al. [8] investigated the methods for panning and zooming using smartphones to support the exploration of 3D data spaces. Hursale et al. [24] proposed a system to recognize gestures in the air using a smartphone's accelerometer. MobiSweep [49] explores the design space for 3D modeling with a smartphone's IMU and touch display.

Our research aims to improve the usability of 3D modeling by using a smartphone with a depth camera as an external controller. As shown in Figure 2, the system increases operability in 3D modeling (multiperson operation, rotation, and sketching by hand gestures)

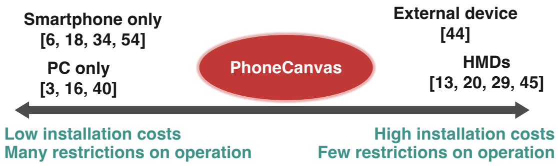


Figure 2: Positioning of our research in previous research.

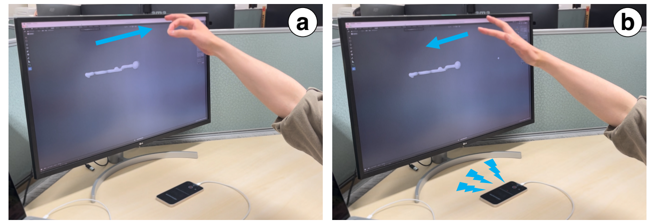


Figure 3: Types of hand gestures: (a) the pinch gesture with the tip of the index finger and the tip of the thumb to draw a line and (b) the gesture other than the pinch gesture to delete a part of an object.

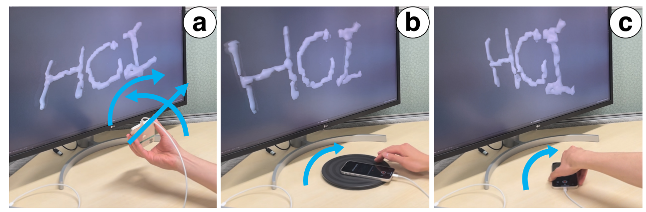


Figure 4: Examples of how to rotate a smartphone: (a) holding the smartphone in the hand, (b) placing it on a swivel stand, and (c) placing it on a desk.

while keeping installation costs low for beginners attempting to carry out 3D modeling.

2.4 Hand-based Creative Interactions

Manipulating objects with hand gestures is useful for humans because of the superior operability and expressiveness of the hands [33]. Research has been conducted on grasping an object [55], remote object manipulation [57] in VR, and AR-based interfaces by Piumsomboon et al. [43]. HandPainter [29] utilizes bare-hand interaction to achieve both 3D freehand sketching [14] and 2D proxy-based sketching.

In the research by Holz et al. [23], the participants used various hand postures and movements to describe a given 3D shape. For instance, they used a spread palm to draw a flat surface diagonally, illustrating the overall shape, scale, and proportion. Kim et al. [32, 33] proposed a scaffold for sketching by introducing a gesture to move the hand sideways for the scaffold. Inspired by the research by Kim et al., we introduced gestures for drawing surfaces by moving the hands sideways.

3 PHONECANVAS

We designed a 3D sketching system called PhoneCanvas by using a depth camera-equipped smartphone as a canvas. This system provides the following basic functions, the designs of which are inspired by conventional canvas interactions, by connecting the smartphone to a PC and complementing 3D modeling in Blender.

3.1 3D Sketching

PhoneCanvas allows users to draw a line and delete a part of an object by performing hand gestures in front of the smartphone (Figure 3). Hand gestures facilitate 3D sketching operations with low learning costs, making the system suitable for rapid prototyping. The system recognizes hand gestures using the depth camera on the front of the smartphone.

The user can draw a line in the space in front of the smartphone through pinch gestures with the tip of the index finger and the tip of the thumb. The user can delete a part of the drawn line with the tip of the index finger by moving their hand while not performing the pinch gesture. To reduce the learning costs, we wanted to avoid increasing the number of gestures. Therefore, we did not create a specific gesture for deletion; instead, objects are deleted upon touch.

3.2 Rotation of the 3D Model

3D sketched objects are anchored to the smartphone. This design allows the user to rotate the 3D sketches by rotating the canvas, i.e., the smartphone (Figure 4). This function brings tangibility to the 3D sketching operation, allowing the user to easily overview the 3D sketches while improving the user's depth perception in mid-air 3D sketching as well as rotation-based sketching, as described in Subsection 7.2. The user can rotate the object in 3-DoF (degrees of freedom). There are three examples of how to rotate a smartphone: holding the smartphone in the hand, placing it on a swivel stand, and placing it on a desk. When the smartphone is held in the hand, it can be rotated in the three axes of roll, pitch, and yaw. When the smartphone is rotated on a swivel stand or on a desk, it can be rotated in one axis. The swivel stand is used to assist in a clean circular rotation, which is useful for drawing circularly regular shapes. The user can quickly switch between rotation styles by simply repositioning the smartphone, enabling the user to select the most suitable style for current needs.

3.3 Feedback

The system provides both visual and tactile feedback to help the user understand what the user is doing in detail. When deleting an object, the smartphone provides vibration feedback (Figure 3b). Additionally, a sphere corresponding to the tip of the index finger, captured by the depth camera, is rendered in Blender. This visual feedback allows the user to accurately determine the position of the index finger in relation to the object.

4 IMPLEMENTATION

This section describes the system implementation. The system architecture is shown in Figure 5. The system collects RGBD images and IMU sensor data from a depth camera-equipped smartphone

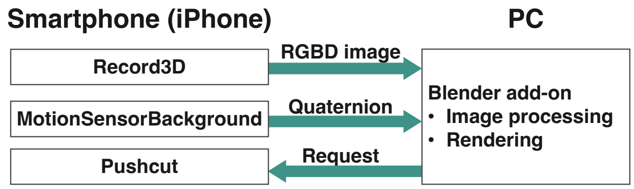


Figure 5: System architecture.

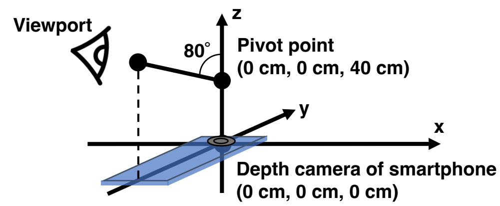


Figure 6: Positions of the smartphone and viewport.

and generates vibrations in that smartphone via a PC. RGBD image capture, IMU sensor data acquisition, vibration generation, and image processing/rendering are conducted through the applications Record3D [50], MotionSensorBackground, Pushcut[1], and a Blender add-on, respectively. We used an iPhone as a depth camera-equipped smartphone. RGBD images are captured using the iPhone's front-facing depth camera (TrueDepth camera). This is because the front camera is better suited than the rear camera's LiDAR for measuring objects that are close. The smartphone's rotation is acquired as a quaternion from its IMU sensor using CMMotionManager [1]. The smartphone's vibration is controlled by sending an HTTP request from the PC to Pushcut when the object is deleted. Pushcut triggers an iOS shortcut that causes the smartphone to vibrate. The RGBD image and quaternion are sent to the PC in real-time, and the Blender add-on performs image processing, rendering, and requests for Pushcut.

4.1 3D Sketching

The RGBD images acquired are used to detect and track the tips of the index finger and thumb in the image processing function. Detection of a hand is performed using MediaPipe [19], and tracking is achieved by selecting the hand closest to its position in the previous frame. The pixel coordinates are transformed into a 3D world coordinate system using the depth image and intrinsic parameters. The function then determines the presence of a pinch gesture based on the distance between the tips of the index finger and the thumb. We used 5 cm as the distance threshold in our first implementation. Finally, the function returns the 3D coordinates of the tip of the index finger, the gesture status (i.e., pinching or not), and the hand tracking ID for each hand.

For drawing a line, the rendering function places a metaball on the 3D coordinate of the tip of the index finger obtained at each frame while the pinch gesture is detected. In addition, metaballs are placed on the grid points between the two consecutive 3D coordinates using linear interpolation to form a line between them.

4.2 Object Rotation Control

The rotation of the object is defined as the rotation of the Blender viewport shown in Figure 6. The coordinate axes are anchored to the smartphone. We place the pivot point at (0 cm, 0 cm, 40 cm). This position is used because the TrueDepth camera works best in the range of 25 cm to 50 cm [28], and thus can track the hand in the range precisely when the user makes the 3D sketches in this range.

[1] https://www.pushcut.io/

To determine the rotation of the viewport, we first transform the quaternion (q_w, q_x, q_y, q_z) obtained from the iPhone CMMotionManager is transformed as follows:

$$\mathbf{q}^* = (q_w, -q_x, -q_y, -q_z).$$

Then, the orientation of the viewport $\mathbf{q}_{\text{front}}$ is calculated as follows:

$$\mathbf{q}_{\text{front}} = \mathbf{q}^* \cdot \mathbf{q}_{\text{default}},$$

where $\mathbf{q}_{\text{default}}$ is a rotation quaternion of angle 80° from z-axis. This calculation ensures that the angle of the viewport corresponds roughly to the angle between the smartphone and the user's eyes in the real world. The user can adjust the distance of the viewport from the pivot point by using the Blender UI.

We implemented the MotionSensorBackground application to obtain the smartphone's rotation in the background. After the user places the smartphone and starts the application to use our system, the relative position from this initial position is tracked.

5 STUDY 1: INITIAL EXPLORATION

We conducted a preliminary study to evaluate the system's functionality by observing the sketching process of how 3D modeling beginners create rapid prototypes of 3D models using the system.

5.1 Participants

Four male graduate and university students (P1–P4) aged 22–23 years volunteered for this study. The participants were beginners who had either never used 3D modeling software or had used it only a few times a year.

5.2 Procedures

The study consisted of two sessions: a specific object sketching session (sketching the string "HCI" and a tree) and a free sketching session. In each session, the participants performed 3D sketching using the system. Each object was described verbally without specifying a specific shape. During the free sketching session, the participants created 3D models based on their own ideas. The participants could freely rotate the smartphone to rotate 3D models, either by holding the smartphone in their hand, using a swivel stand, or placing the smartphone on a desk. The threshold for pinch gestures was 5 cm. We measured the time taken to complete the sketching tasks, starting when the author said "start" and ending when the participant said "end." After the study, the participants completed a System Usability Scale (SUS) [7] questionnaire and participated

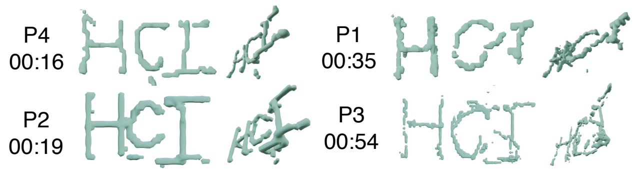


Figure 7: Examples of "HCI" sketched by the participants and the time taken to sketch (mm:ss).

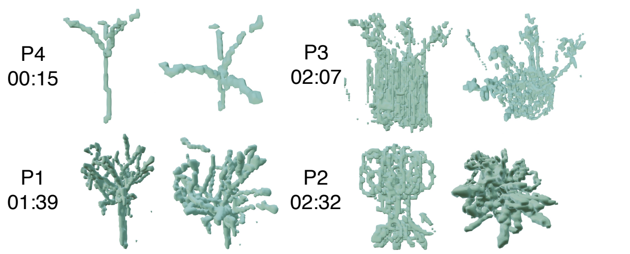


Figure 8: Examples of trees sketched by the participants and the time taken to sketch (mm:ss).

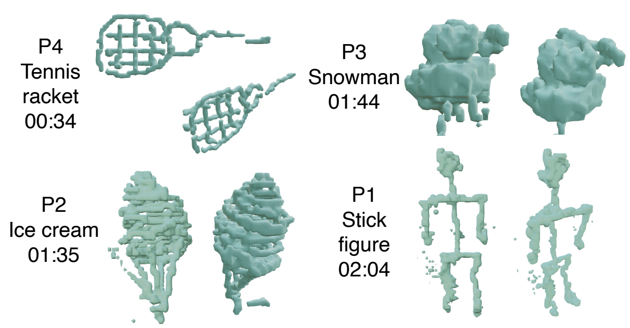


Figure 9: Examples sketched by the participants and the time taken to sketch (mm:ss).

in a semi-structured interview about hand gestures, rotation, feedback, and the sketching process. All tasks were performed using an iPhone 12 mini and a 14-inch MacBook Pro.

5.3 Results

5.3.1 Sketching session. In the sketching session for the specific object, the mean times taken to sketch "HCI" were 00:31 (SD = 00:17) and trees were 01:38 (SD = 00:59), respectively. Examples of "HCI" and trees sketched by the participants and the time taken to sketch them are shown in Figure 7 and 8, respectively. In the free sketching session, the mean time for freely sketching 3D shapes was 01:29 (SD = 00:34). The examples sketched by the participants and the time taken to sketch them are shown in Figure 9.

The SUS scores for P1, P2, P3, and P4 were 92.5, 57.5, 10.0, and 75.0, respectively (M = 58.8, SD = 30.8).

5.3.2 Interview results. The results of the interviews regarding hand gestures, rotation, feedback, and sketching processes are presented below.

Hand Gestures. Sketching with hand gestures was found to be user friendly (P1, P4), enhancing ease of use. P1 commented that "*Hand gestures were generally easy to use.*" However, the delete gesture was considered difficult to use (P1, P3, P4), and lines were drawn when not intended (P2). P4 commented that "*Pinch gestures were easy to use, but caution is needed, as overlapping parts disappear when touched.*"

Rotation. The swivel stand was frequently used by P2. Participants found it useful in getting a comprehensive view of the completed objects (P1, P4) and for depth verification (P2). For example, P1 commented that "I often rotated the object after completion." and P2 commented that "The swivel stand was often used. Rotation by hand was not used much. Rotation was used for depth verification."

Feedback. Participants P1, P3, and P4 mentioned that vibration feedback was unnecessary. P3 and P4 commented that "*I felt no problem without vibration because I could see it with my eyes.*"

Sketching Process. The sketching process was described as easy and approachable (P1, P2), allowing for the immediate drawing of whatever came to mind (P2, P4) and enabling more freeform shapes (P3, P4). P4 commented that "*Compared to Blender, it is good that you can draw free strokes in 3D. It is good that you can draw what you think of immediately.*" However, it was commented that the system was unsuitable for detailed work (P2) or for drawing predefined shapes, such as cubes and spheres (P3). P2 also commented that "*I felt it was easier to use than Blender. I could easily draw what was in my head. Blender is better for drawing precise objects.*"

5.4 Discussion

During the sketching session for the specific object, the participants sketched "HCI" in an average of 31.2 seconds and the tree in an average of 1 minute and 38.8 seconds using the system. In the free sketching sessions, the participants created 3D models based on their own ideas within approximately three minutes. These results indicate that even beginners can perform 3D sketching with the system, suggesting that the system could be used for rapidly prototyping various 3D models.

However, the mean SUS score of the system was 58.75, suggesting room for improvement. Notably, P3 had a significantly low SUS score of 10.0, indicating a wide variance in ease of use among the participants. In the interviews, the participants pointed out problems with hand gestures because of unexpected movements, indicating a need for improvement. Specifically, a function allowing users to adjust the distance threshold between the tip of the index finger and the thumb, which is used for recognizing a pinch gesture, is required. For the vibration function, some participants felt that visual feedback alone was sufficient, suggesting the possibility of removing the vibration function. In addition, the system specializes in 3D sketching using lines; adding functions for quickly creating 3D shapes is also needed.

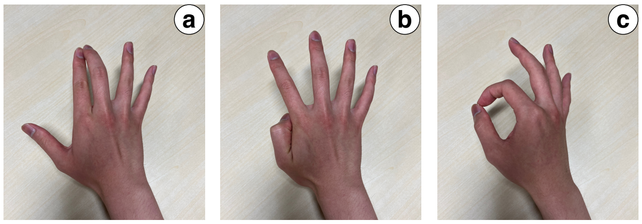


Figure 10: Types of hand gestures: (a) pen gesture, (b) delete gesture, and (c) surface gesture.

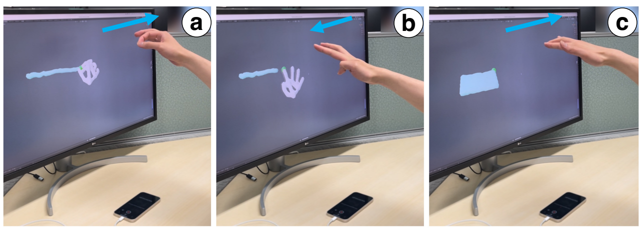


Figure 11: Hand gesture behavior: (a) pen gesture behavior, (b) delete gesture behavior, and (c) surface gesture behavior.

6 SYSTEM REFINEMENT

Based on the results of Study 1, the following functions have been added or changed.

6.1 3D Sketching

To expand the range of 3D sketching, the system supports drawing surfaces in addition to lines. A line is drawn from the tip of the index finger to the wrist when the user touches the tip of the index finger to the tip of the middle finger (surface gesture; Figure 10a); moving the hand in this state draws a surface. This gesture is based on the work of Kim et al. [32]. In Study 1, the participants commented on the difficulty of using the delete gesture. In response, we added a new gesture for deleting an object drawn: touching the third joint of the index finger with the tip of the thumb (delete gesture; Figure 10b). The gesture for drawing a line remains unchanged (pen gesture; Figure 10c). Figure 11 shows the behavior of the three gestures. Additionally, metaballs, which were previously placed at grid points, are now placed at arbitrary points, allowing for finer placement and more precise 3D sketching.

6.2 Rotation of the 3D Model

We added a window to show depth for easy user comprehension of the operation. Specifically, a 90° horizontal viewport window was added on the right side of the system window as shown in Figure 12.

The calculation of the viewport is as follows:

$$\mathbf{q}_{\text{side}} = \mathbf{q}^* \cdot \mathbf{q}_{\text{add}} \cdot \mathbf{q}_{\text{default}},$$

where $\mathbf{q}_{\text{add}}$ is the quaternion for the 90° horizontal rotation.

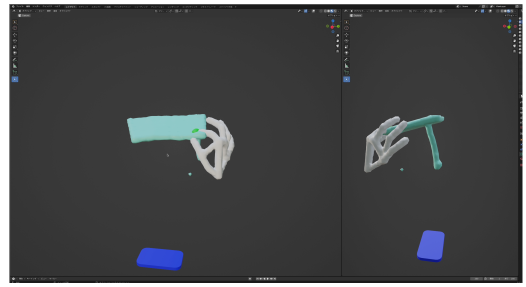


Figure 12: Overall visual feedback of the system.

6.3 Feedback

Enhanced feedback makes it easy to understand the user's operations. Specifically, the entire user's hand and the smartphone are displayed, and depth windows are added. We added visual feedback of the user's hand to allow users to check their hand movements on the screen, eliminating the need to look back and forth between the screen and their hands. The hand-shaped object in Figure 12 represents the visual feedback of the whole hand, and the blue object represents the smartphone. The window on the right side is the depth window. Vibration feedback was removed because Study 1 participants indicated it was unnecessary, and the smartphone would move because of vibration when placed on a desk.

We added visual feedback of the entire user's hand and the smartphone (blue rectangle), as shown in Figure 12, allowing the user to check the hand movement on the screen by eliminating the need to look back and forth between the screen and the hand. Vibration feedback was removed because participants indicated it was unnecessary in Study 1, and the smartphone would move due to vibration when placed on a desk.

7 APPLICATIONS

The refined system can be used for rapid prototyping, rotation-based sketching, modifying existing objects, and collaborative work.

7.1 Rapid Prototyping

Users can create and delete lines and surfaces in the space in front of the smartphone. The system, composed only of a smartphone and a PC, makes it easy for users to get started with 3D modeling. Additionally, users can perform 3D sketching while tangibly rotating the viewport using the smartphone's rotation

7.2 Rotation-based Sketching

Users can use the smartphone as the origin of the canvas and rotate it to perform rotation-based sketching. Users can create regular circular objects by rotating the smartphone with one hand while sketching with the other. Figure 13 shows a user sketching a plate by anchoring their hand in space and rotating the smartphone on a swivel stand. Figure 14 shows a user sketching a tree branch by rotating the swivel stand while moving their hands diagonally upward.

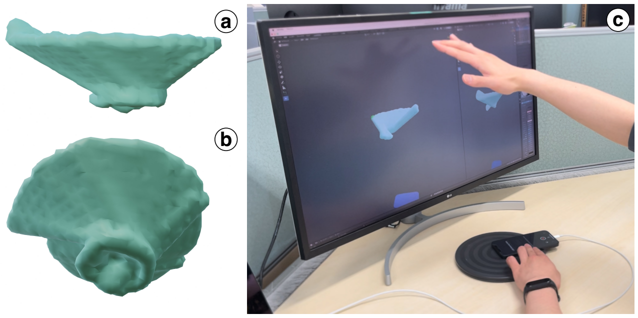


Figure 13: Rotation-based sketching of a plate: (a) the plate viewed from the side, (b) the plate viewed from below, and (c) the user creating it through rotation-based sketching.

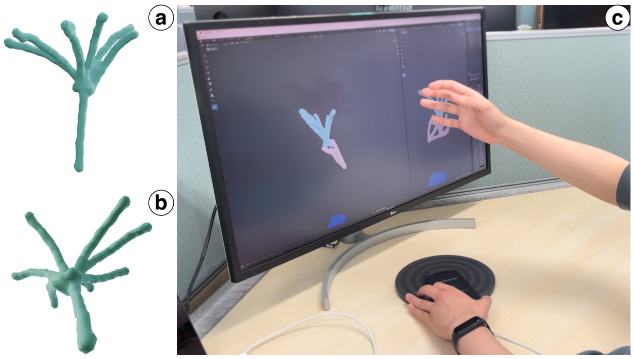


Figure 14: Rotation-based sketching of a tree: (a) the tree viewed from the side, (b) the tree viewed from below, and (c) the user creating it through rotation-based sketching.

7.3 Modification

The system allows users to modify existing 3D models, such as adding annotations. Figure 15 shows how the mouth and ears of the Blender Suzanne are annotated. This feature would promote discussions in the fields of character design, architectural design, and product design. Users can also add new 3D shapes to existing models. Figure 16 shows how the shape of the ears and the cheek area has been changed for the existing object (Blender Suzanne).

7.4 Collaboration

The system enables multiple users to collaborate by tracking multiple hands captured by the depth camera. Figure 17 shows multiple users using the system in a discussion. Several people can simultaneously draw 3D strokes by performing hand gestures in the space in front of the smartphone. Cooperative work is also possible, with one person using the mouse and another using the smartphone.

8 STUDY 2: IN-DEPTH EVALUATION

We conducted a study with 3D modeling beginners to test the performance of the improved system, focusing on the time spent working alone and in collaboration.

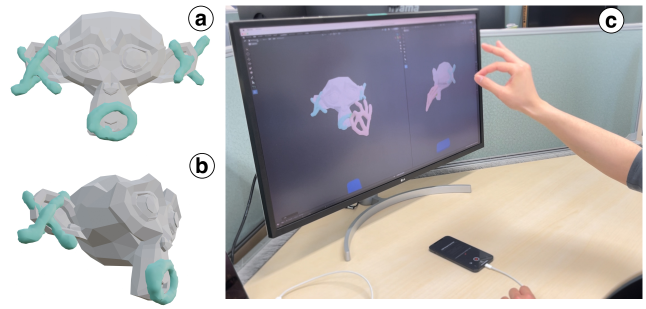


Figure 15: Annotation of existing objects: (a) the annotated object viewed from the front, (b) the annotated object viewed from the side, and (c) the user annotating an existing object (Blender Suzanne).

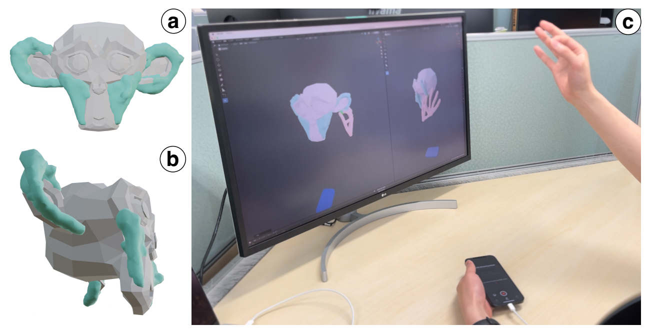


Figure 16: Modification of existing objects: (a) the modified object viewed from the front, (b) the modified object viewed from the side, and (c) the user adding a new 3D shape to an existing object (Blender Suzanne).

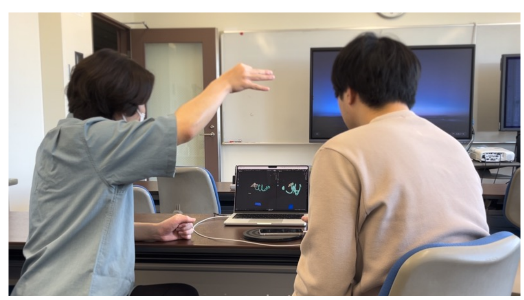


Figure 17: Discussion of 3D shapes using PhoneCanvas.

8.1 Participants

We recruited 12 university students (10 male, 2 female) aged 21–24 years (M = 22.7, SD = 0.98). The participants were beginners who had either never used 3D modeling software or had used it only once a year. Each participant received 1920 JPY as compensation, and the study took approximately 120 minutes.

8.2 Procedures

The study had two tasks, which the participants experienced sequentially.

Task 1 The 3D shapes of a desk, a plate, and a free object were sketched using the system to test basic operability. Each object was described verbally without specifying a specific shape. A swivel stand was used to create the plates for smooth rotation.

Task 2 To investigate the performance of collaborative work using the system, pairs of participants were instructed to devise and sketch a new light fixture while engaging in discussion. The participants (P1–P12) were divided into six pairs (P1–P2, P3–P4, ..., P11–P12) for this task.

In each task, the participants performed 3D sketching using the system. We measured the time it took to complete the sketching, starting when the author said "start" and ending when the participant said "end." Before each object in Task 1 was created, a five-minute practice session was held. The threshold for hand gestures was adjusted during practice if there was misrecognition, resulting in 3 cm–5 cm. All participants performed Task 1, followed by Task 2, with a five-minute break between them. After each task, the participants completed a questionnaire about the SUS [7] and the NASA Task Load Index (NASA-TLX) [21]. For Task 1, semi-structured interviews were also conducted on hand gestures, rotation, feedback, and the sketching process; for Task 2, semi-structured interviews were conducted on the sketching process in discussions. All tasks were performed using an iPhone 12 and a 14-inch MacBook Pro.

8.3 Results

8.3.1 Results for Task 1. The sketched desk, plate, and free object are shown in Figures 18a, 18b, and 19, respectively. The mean time taken to sketch the desk, plate, and free objects were 00:58 (SD = 00:30), 01:29 (SD = 00:53), and 01:37 (SD = 01:13), respectively. The mean SUS score was 62.7 (SD = 10.6). The total NASA-TLX score was 60.0 (SD = 14.7).

Desk. For the participants who completed the task quickly (P12, P10, P9, P6), there were noticeable issues, such as incorrect positioning of legs, uncorrected mistakes, and a simplification of leg shapes. For the three participants with moderate completion times (P5, P2, P1), no significant visual defects were observed. The five participants who took the longest (P4, P11, P3, P8, P7) showed evidence of error corrections.

Plate. Unlike the desk task, it was difficult to distinguish between the quick- and moderate-speed groups (P3, P9, P10, P4, P5, P7, P6, P1). Those who took longer (P8, P11, P2, P12) exhibited corrections to their mistakes.

Free Object. The quick-speed group (P9, P8, P6) created objects with simple shapes. Similarly, the two individuals who took a long time (P12, P11) also produced simple objects but spent much time on them. The moderate group (P3, P4, P5, P2, P7, P10, P1) either made numerous corrections to simple objects, sketched meticulously, or created complex objects.

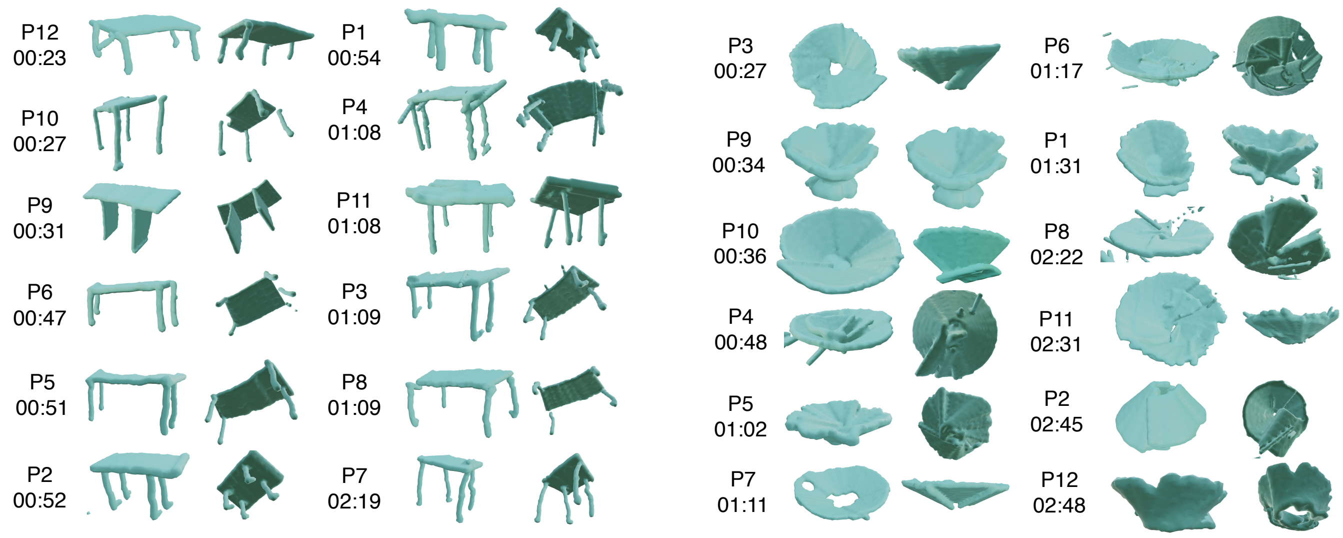
The following are the results of the interview.

Hand Gestures. The system was found to be intuitive (P4, P12, P5, P2, P1). P1 commented that "*The intuitive sketching experience was enjoyable because there was no need to switch between shapes using buttons or the mouse.*" Additionally, P4 commented that "*Compared to conventional 3D sketching methods, PhoneCanvas was intuitive to operate because there was no need to learn shortcut operations to instantly switch between camera operations and object placement.*" P3, P9, and P11 appreciated the ease of surface gesture, highlighting the user friendly interface. P3 and P9 commented that "*it was especially easy to use surface gesture.*" P9 claimed the need for enhanced depth perception when manipulating lines. P9 commented that "*The surface gesture is intuitive, but the pen gesture may require depth perception.*" Issues with gesture recognition were reported by P9, P11, and P8. P8 commented that "*On more than one occasion, when a finger was placed outside the range of the camera, it was recognized as a hand gesture for deletion, causing part of the created object to disappear.*" P10 had complaints regarding occlusions. P6, P11, and P12 experienced arm fatigue, participant P3 did not experience this issue. P6 commented that "*The fingers not used for gestures had to be constantly extended, which could be tiring after prolonged use.*"

Rotation. P1, P2, P6, P7, and P10 found the rotation feature useful for their interactions. P1 and P7 commented that "*I used the rotation function mainly to check the sketched object, and they could easily operate the camera.*" On the other hand, P3, P5, and P6 reported that the cable that connects the smartphone and PC often obstructed their movements, reducing efficiency. They commented that "*The smartphone slipped on the swivel stand, as it was pulled by the cable.*"

Feedback. All participants (P1–P12) found the full-hand display feature understandable. The sideways window was rarely used by P9, yet P5 and P7 found it beneficial. P5 and P7 commented that "*I could perceive the depth of their hands because the entire hand was displayed on the screen and rendered using two screens.*"

Sketching Process. The system was deemed user friendly and intuitive (P4, P12, P5, P2, P1). P4 commented that "*The conventional system requires moving the camera and placing objects in detail, which requires learning various shortcut keys. However, this system can be operated intuitively once the user learns how to operate it.*" P6 highlighted its suitability for prototyping and use during meetings. P6 commented that "*Although it is difficult to draw as precisely as with conventional CAD, I thought it would be useful for prototyping or using as a whiteboard during meetings.*" P10 and P7 mentioned ease of use with increasing familiarity. P7 commented that "*I think it would be a very good tool for any beginner since I could do it as if I were drawing a picture in two dimensions once I got used to it.*" P3 suggested that the system suits organic rather than inorganic designs. P1 noted difficulties in perceiving depth. P1 commented that "*I found it surprisingly intuitive to operate. However, I felt that it was difficult to grasp space in three dimensions on the screen.*" P9 found it difficult to switch between two screens. P9 commented that "*The multiple views of the object made it difficult to manipulate because I had to alternate between them.*" P11 recommended the inclusion of interpolation features. P11 commented that "*I felt it would be better if there were interpolation of straight lines and curves, which would make it easier to operate intuitively.*" P8 described the system as difficult to operate.



(a) desk **(b) plate**

Figure 18: Objects created by the participants sorted in ascending order of time (mm:ss) spent sketching.

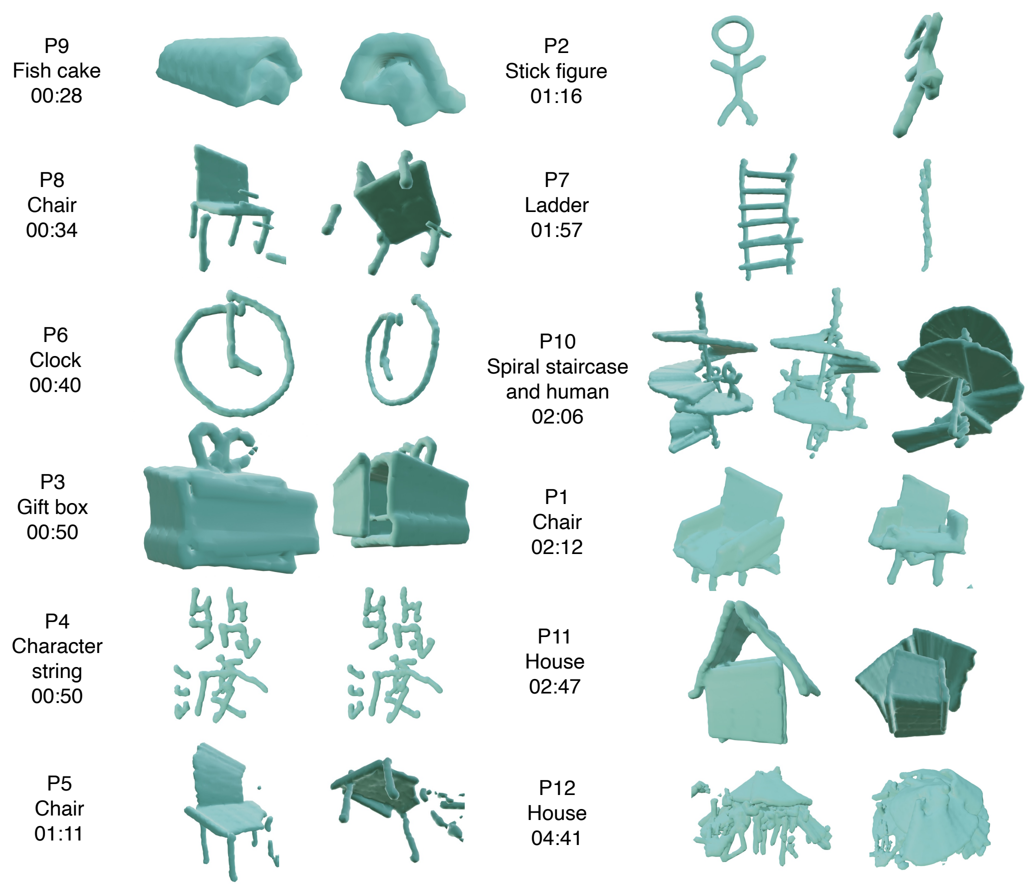


Figure 19: Free objects created by the participants, sorted in ascending order of time (mm:ss) spent sketching.

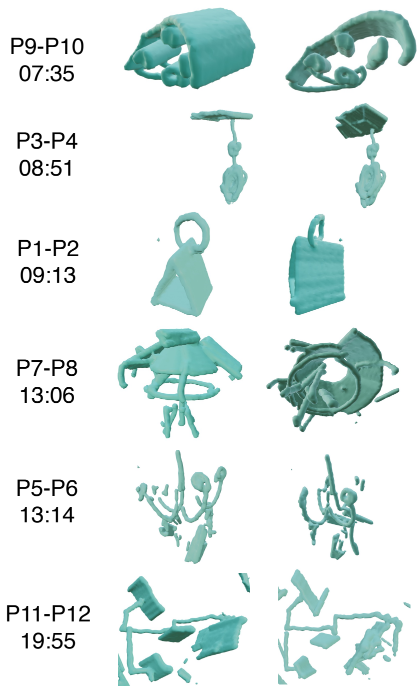


Figure 20: Light fixtures created by the participants, sorted in ascending order by the time taken to sketch (mm:ss) in Task 2.

8.3.2 Results for Task 2. The sketched objects are shown in Figure 20. Pairs P1–P2, P3–P4,..., P11–P12 created triangular light, ceiling-hung light, chandelier, indirect light, fluorescent light combined with another fluorescent light, and several flat lights combined, respectively. The mean time taken to sketch was 11:59 (SD = 04:31), the mean SUS score was 63.5 (SD = 12.1), and the total mean NASA-TLX score for Task 2 was 64.3 (SD = 14.0).

The following are the results of the interview. The system was found to be user friendly as a discussion tool (P1, P2, P3, P4, P6, P7, P11, P12). P6 commented that "*It was very easy and convenient to share information because I could quickly share the images I was thinking about.*" P1 commented that "*I enjoyed the discussion because I could intuitively visualize in front of me the ideas I had been talking about in words. I was a little nervous about sketching while being watched by the other participants because I was not yet familiar with the sketching function and was not confident with it.*" P8 and P9 also commented familiarity with the system was necessary. Additionally, it was used for sketching 3D shapes and doodling (P3, P4, P5, P6, P7). P3 commented that "*It was easy to use the system for discussion purposes. It was easy to use because we used it as a memo rather than to create something concrete.*"

9 DISCUSSION

In Task 1 of Study 2, the participants sketched a desk for 58 seconds, on average, and a plate for 1 minute and 29 seconds, on average, using the system. This result suggests that even beginners can complete 3D sketching quickly. For free object sketching, the participants sketched 3D models based on their own ideas for 1 minute and 37 seconds, on average. Although the sketching time varied among users, even beginners could complete 3D sketching within about 2 minutes. This suggests that the system can be used for rapidly prototyping various 3D models. Furthermore, in Task 2, the participants were able to perform 3D sketching for 11 minutes and 59 seconds, on average, while discussing, and they expressed that the system was a user-friendly tool to use during the discussions. This result suggests that the system feature allowing for multi-person operation in real-time 3D sketching can be used for discussions. However, since it has not been compared with other methods and systems, it cannot be definitively stated that it is superior to existing methods and systems. In Study 2, unique features were observed, such as unexpected forms of collaboration where one person gestured and another rotated a smartphone. However, as a tool specifically for collaboration, it is still immature. Additionally, as the system uses a front camera on a smartphone, the field of view is limited, and the current implementation can track two hands simultaneously. The system is limited to 3-DoF rotation, allowing for sketching through the movement of the smartphone; however, it does not support moving objects through the parallel movement of the smartphone.

The system allows beginners to create 3D models easily and quickly. However, the appearance of these models is inferior to those created with previous 3D sketching systems, with rough lines in particular. In our system, the position of the hand was estimated from the image and depth data, and thus, the accuracy of the hand position estimation was low. In addition, the lines became rough because of hand tremors. The low recognition accuracy of images also led to the false recognition of hand gestures, hindering user performance and satisfaction. The current implementation uses a constant distance threshold for finger contact recognition, which has proven problematic because of individual variations in hand shapes and gestures; adopting machine learning-based gesture recognition might offer a robust solution. In addition, the interview of Study 2 indicated that depth perception was still problematic; combining our method with other approaches(e.g., [52]) would be necessary to solve this.

10 CONCLUSION

In this paper, we presented PhoneCanvas, a system that supports 3D modeling on a PC using a depth camera-equipped smartphone as a canvas. The system allows sketch-based modeling by hand gestures, object rotation by smartphone rotation, and cooperative work, all at low installation costs. The results of the user study showed that beginners could quickly create 3D models and use the system in discussions. Future work includes improving gesture recognition accuracy, enhancing the user interface, expanding feedback, and conducting comparative user studies with others.

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