UbiSurface: A robotic touch surface for supporting mid-air planar interactions in room-scale VR

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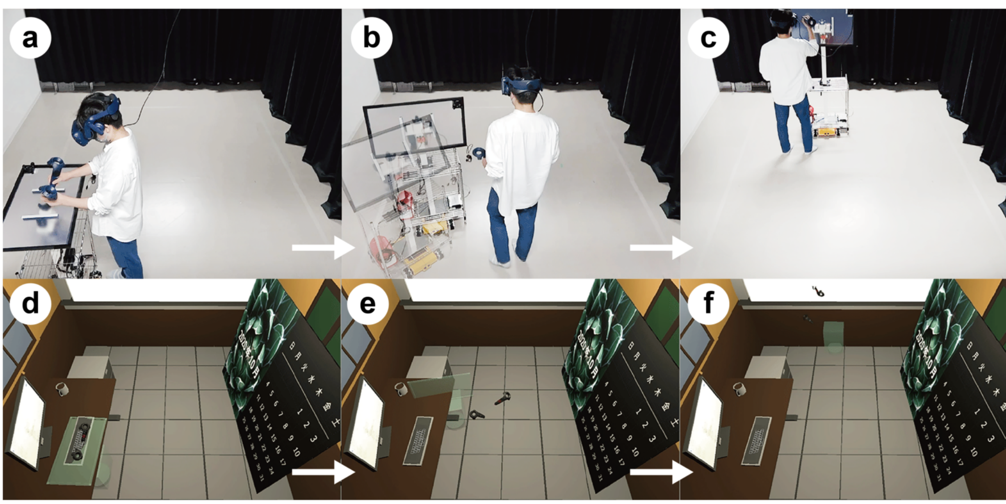

Fig. 1. The user interacts with the VR environment through UbiSurface. a,b,c) UbiSurface follows the user in the real world and supports his input. d,e,f) UbiSurface is represented by green props in the virtual world during user interaction.

Room-scale VR has been considered an alternative to physical office workspaces. For office activities, users frequently require planar input methods, such as typing or handwriting, to quickly record annotations to virtual content. However, current off-the-shelf VR HMD setups rely on mid-air interactions, which can cause arm fatigue and decrease input accuracy. To address this issue, we propose UbiSurface, a robotic touch surface that can automatically reposition itself to physically present a virtual planar input surface (VR whiteboard, VR canvas, etc.) to users and to permit them to achieve accurate and fatigue-less input while walking around a virtual room. We design and implement a prototype of UbiSurface that can dynamically change a canvas-sized touch surface's position, height, and pitch and yaw angles to adapt to virtual surfaces spatially arranged

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at various locations and angles around a virtual room. We then conduct studies to validate its technical performance and examine how UbiSurface facilitates the user's primary mid-air planar interactions, such as painting and writing in a room-scale VR setup. Our results indicate that this system reduces arm fatigue and increases input accuracy, especially for writing tasks. We then discuss the potential benefits and challenges of robotic touch devices for future room-scale VR setups.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**.

Additional Key Words and Phrases: virtual reality; haptics; inflatable; mobile robots; distributed encountered type haptics

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1 INTRODUCTION

Room-scale VR has attracted increasing attention for its ability to allow HMD users to perform natural walking while interacting with virtual objects fixed throughout a room. Compared with traditional locomotion interfaces using gestural input (e.g., teleportation with lay casting), HMD users' natural walking makes their VR experience more immersive [14, 53, 60]. Example scenarios include life-size scientific data visualization, architectural design, furniture design, art studios, and offices. In these scenarios, HMD users can walk around spatially visualized data, 3D models, canvases, and information displays, where walking among the contents should provide better spatial understanding of the room structure and properties of the contents such as scale, arrangement, and shape.

However, the current primary input mechanisms, which rely on mid-air interactions, face the challenge of overcoming a significant burden on the user's arm, which quickly increases as hand control accuracy progressively degrades [8, 15]. This phenomenon is called the Gorilla Arm Syndrome [9, 15, 31, 40] and is well known as one of the traditional unsolved issues of current off-the-shelf HMD setups. Among the various types of common mid-air interactions (e.g., postures and gestures), we focus on planar interaction. Examples include pointing, steering, typing, writing, and drawing, all performed on virtual surfaces (e.g., software keyboard, canvas, notebook). We believe such planar input on virtual surfaces is crucial in workspace activities such as content design, depiction, and documentation. Compared to gestural command input with rougher hand motions, writing a short sentence or sketching a brief diagram on virtual notes requires more precise hand control, significantly increasing whole-arm fatigue in the air.

To mitigate this issue, researchers have proposed several solutions. The most naive one is placing physical guidance (i.e., a prop) in the environment to support users' elbows or fingers during mid-air interactions [24, 62, 64]. However, these methods require careful preparation of props beforehand. The second is designing interaction techniques that avoid keeping the arms at high areas by remapping the motor input to the visual content input [22, 36] or the use of eye-gaze information together with hand input [72]. While such indirect input mechanisms can be easily installed, they generally force users to adapt to unconventional interaction styles, many of which have not proven that precise input can be correctly made. The third is adding a touchscreen held in the user's non-dominant hand [7, 18, 45, 55, 67, 68], where the user can input the touch motions of the dominant hand onto the touch surface. Although this method can support fundamental planar inputs, it significantly restricts the user's posture and interaction possibilities (e.g., bi-manual input). Consequently, while each of the mentioned approaches have their limitations, we want to seek more effective solutions while retaining their familiar direct interactions with a natural posture.

Besides mid-air interactions, our survey identified that ungrounded encounter-type haptic devices using moving physical props have been proven effective in providing haptics of dynamic VR content around the room [12, 46, 56, 69, 71]. Although, their primary goal differs from ours, the basic properties of their prototypes (e.g., human-sized props, locomotion capabilitites) could be leveraged to support the user's arms in room-scale VR experiences.

In this work, we propose UbiSurface, a self-actuated robotic touch surface that can dynamically reposition itself to physically present to the user a virtual planar input surface (e.g., VR whiteboard or VR drawing canvas) arranged in a virtual room and to support the user's accurate and fatigue-less mid-air planar input (writing, typing, etc.) within room-scale VR. This touch surface consists of three types of actuators to achieve five types of motion freedoms on the touch surface, including basic horizontal translations (x, y) and yaw and pitch rotations, rendering variously arranged virtual planar surfaces in the virtual room. This robotic touch surface is basically positioned around the walking VR users. In the case of prolonged mid-air interaction, it is automatically repositioned and reconfigured to provide a physical touch surface that matches the required virtual surfaces (e.g. whiteboard, memo pad, 3D model).

Fig. 1 illustrates a use example of UbiSurface in virtual offices. The user initially types text using a virtual keyboard on a desk (Fig. 1 a). He then comes to the whiteboard next to the desk (Fig. 1 b) to draft his concepts using handwriting (Fig. 1 c). He can also come back to continue typing text. At every step, UbiSurface's movements and surface reorientation allow it to continue to support the user's sequential mid-air interactions occurring at different positions and angles. In this paper, we discuss UbiSurface's design in detail and report its first prototype using a set of actuators and off-the-shelf materials. We then conduct a technical study to clarify its positioning performance as well as a user experience study that clarifies how it supports primary mid-air interactions.

The contributions of this work are 1) proposing UbiSurface, a new repositioning and re-configuring robotic touch surface supporting a user's mid-air planar interactions at various locations in room-scale VR, 2) detailing its first prototype and reporting technical performance, and 3) demonstrating how it supports the user's primary mid-air-interaction scenarios through a user study.

2 RELATED WORK

Here, we briefly outline three domains of prior work related to our proposal: mid-air interaction, physically supported VR interaction, and robotic props.

2.1 Mid-air interaction

Numerous interaction styles can be used in room-scale VR setups, including hand-held controllers (e.g, [29]), hand gestures (e.g, [1]), and NUIs (natural user interface) (e.g., [35, 37, 50]). NUIs are generally designed for different input strategies, while a hand controller or gestures allow for planar interactions (e.g., typing, drawing, annotation). Although these modes form the current mainstream, several studies have pointed out that they can cause arm fatigue and inaccurate input. For example, Arora et al. reported that the accuracy of mid-air interaction is lower than that with a physical surface or guide [8]. Similar effects also arise in the case of 3D sketching without any physical support, which does not permit detailed drawing experiences [7, 33, 64]. These issues are often called the "Gorilla Arm Syndrome," which makes prolonged mid-air hand interaction significantly more difficult [9, 15, 26, 31, 40]. To address this challenge, several interaction techniques have been proposed to allow users to perform overhead content manipulation at a more comfortable arms-down posture. For example, input offsets have been explored where VR users' input in arm-down posture (such as chest or belt level) is adapted to content manipulation at eye-level height [13, 22, 36]. Recent advances in eye-tracking systems within VR headsets offer interaction possibilities that combines user's eye-gaze with hand-based selection methods [65, 72], which have been reported to be effective for mitigating arm-fatigue due to more comfortable arm postures [72]. Such indirect interactions are quite powerful, yet have not been well studied in teh context of writing and drawing.

2.2 Physical support for mid-air interaction

To support mid-air interactions, the effectiveness of physically supporting the user's arm or fingers has been confirmed [8, 41, 64]. Specifically, the use of an armrest has been reported to be effective in mitigating arm fatigue [24, 62]. However, an issue with this approach is that the user's arm postures are restricted to the supported joints, and appropriately sized and shaped physical props need to be anchored in the work area beforehand. Despite the limitations, this simple idea of adding physical support has been explored for various types of interaction techniques.

First, tracked tablet devices have been employed in the VR interaction (e.g., Virtual notepad [48], Slicing-Volume [45], VRSketchIn [18]) to enable more accurate pointing and VR sketching input on the surface. TabletInVR [55] proposed a range of object manipulations by leveraging a multi-touch tablet's capabilities. Wang et al. [67, 68] proposed attaching a multi-touch screen tablet to the non-dominant forearm. Smartphones are frequently used as a VR controller in many studies (e.g., Phonetrolle r[39], VRySmart [38], text typing [11], and navigation [17]. These approaches generally raises an additional issue of the non-dominant hand's arm fatigue and precise input is still difficult due to the instability of the touchscreen held in the hands.

The second approach uses wearable haptic or force devices. Traditionally, passive or actively controlled strings or wires have been widely studied (e.g., SPIDER-W [47], HapticSphere [66], STRIVE [5]). However, their original idea was to provide the users with force feedback to improve the contact interaction with VR content. While such devices often have sufficient stiffness, the range of support is typically narrow, and wearing them is cumbersome and does not allow for on-demand use of the device.

The third approach uses the user's own body as a physical surface. For example, ActiTouch [73] and HandPainter [32] proposed planar content interactions by touching the hand or forearm of the user's non-dominant hand with the dominant hand's fingertip. Handwriting Velcro is a touch sensor supporting handwriting in an AR scenario, and it can be fixed on various body parts [21]. However, similar to the first approach, the interactive surface size is generally narrow, raising concerns regarding non-dominant hand fatigue.

Finally, we can also consider utilizing a large grounded touchscreen supporting surface touch interactions [16, 54] or providing force feedback to users through the use of actuators (e.g., [51]), however these concepts were designed for fixed desktop VR.

Therefore, we find clear benefits of the additional physicality. Our approach also adds a physical touch surface, which stands on the shoulders of these prior works but significantly expands them by introducing a unique motion mechanism and a sufficient surface size that can be effective in office-like room-scale VR experiences.

2.3 Robotic haptic device

To represent haptic sensation or force when interacting with virtual content, robotic haptic devices have been introduced. Most of them are originally designed for improving the realism of the virtual world. However, in terms of the use of external robots and adding physicality to the VR experience, this research topic is strongly related to our approach.

While there are numerous robotic haptic devices, here we focus on encounter-type devices in which props run themselves to automatically represent the haptic sensation when the user's finger contacts the virtual content [43]. For room-scale VR scenarios, the haptic presentation of entire room objects is challenging because the robotic arm's range is generally limited and such a robot tends to be spatially fixed (e.g., [6, 27, 42, 63]) or robots are designed for tabletop-size content(e.g., [52, 57]). Consequently, many researchers have used drones to offer room-scale haptic representation [2, 3, 23, 59, 70]. However, their stability in the air is not sufficient for supporting mid-air interaction.

EncounterLimbs [28] uses a mix of encounter-type robot and wearable approaches. The VR user wears a robotic backpack that has a two-joint arm. A tablet-size plate is fixed to the arm's endpoint and placed within the user's arm reach. The plate is automatically adjusted to correctly represent physical contact when the users touch virtual objects fixed in the virtual world. This device might sufficiently support the user's arm in the air, since it supports 28.4 - 112 N, depending on the pushing locations. However, it still has a limited surface size, and based on our concept, such additional weight to the body might negatively affect the user's workload.

The use of ground robots has been increasingly explored. For example, human-sized robotic walls and props representing the haptics of the virtual room infrastructure have been investigated [25, 56, 69, 71]. These use moving robots around the room, which can basically follow walking users in a room-scale VR system, and its enclosure physically represents the virtual surfaces. These researchers generally focused on an algorithm of encounter-type prop control, providing proper haptic sensations or improving the experience's realism. CoboDeck is a recently proposed room-scale haptic system using a high-end collaborative mobile robot with a robotic arm [46]. While the motivation and the robot's motion degree of freedom resemble ours, their primary contribution was a safe and effective robot control mechanism, and they did not examine any issue of user experience. In summary, robotic devices' usage techniques and potential for assisting users' mid-air interactions remain largely undefined.

3 UBISURFACE

As described at the previous section, the design of a robotic prop supporting the user's mid-air planner interactions in free-walking scenarios has not yet been explored and examined. Thus, We propose UbiSurface, a robotic touch surface that provides HMD users a stable physical touch panel at the same location and angle to the virtual surface that they touch, without interfering with their free walking in the room-scale VR.

Similar to existing robotic haptic devices, we also rely on the external moving robot approach, where the user does not need additional devices, and the robot's relatively large enclosure would offer stable physical support compared to their on-body props. The idea of using an external robot might increase the overall system setup, but it might eventually allow for more flexible operation than the wearable or additional controller approaches. For example, the user's setup can be generally compact, and they can call up such robotic devices on demand, depending on the need for mid-air interactions. Furthermore, robots are being increasingly deployed in our homes, offices, and workplaces (e.g., cleaning robots, warehouse robots, assist robots), which also supports our basic concept. In the following, we discuss our scope, design considerations, and implementation.

3.1 Assumption and scope

We first set our assumption and scope for developing feasible systems.

Our assumption is that VR users are mainly standing or walking in primary use cases of room-scale VR such as office, design studio, and life-size data visualization. Presently, we do not support sitting users, based on our aim to simplify hardware design.

Our scope covers mid-air planar interaction such as sketching and writing experiences with fingers or writing tools, which are key actions for VR office users.

Our goal is to mitigate arm fatigue and support accurate mid-air planar input. While our system offers haptic feedback, immersion or realism is not our main concern. Therefore, we do not aim toward achieving the ideal encounter-type haptic device, since its fundamental technical elements, such as control and user goal prediction algorithms, have been extensively studied in previous works(e.g., [46, 56, 57, 71]) whose knowledge could be incorporated later if needed. Another technical consideration is safety, which is particularly brought by our motivation and robotic device approach. We have configured a relatively large and heavy robotic device (around 20 kg, see Fig.2 right) with moving parts that may reach the user's chest or shoulders. Such a robot cannot operate faster than 0.4 m/sec due to industrial regulations regarding collaborative robots (Transient Contact Speed Limits, ISO TS 15066:2016 [30]), which we should follow at this early prototyping stage.

3.2 Design considerations

We set the following four design requirements.

1. Physical input support: In the real world, people adjust their hand motor control based on physical reaction to touching objects. The issue with mid-air interactions in VR systems are a result of mismatches between VR and real-world sensory feedback, resulting in inaccurate manual dexterity. To correct this mismatch, we add a physical surface so that users can optimize their arm control by moving their writing tool on a physical surface.

2. Canvas-size interaction surface: Supposing basic scenarios and activities using fingers or writing materials (pen, brush, etc.) in virtual office contexts, we believe that a canvas-sized surface is required to allow users to apply both hands to text typing, writing a short sentence, and illustrating a diagram on a single surface. Although numerous previous work have used smartphones (e.g., [11, 38, 39]) or tablet touchscreens(e.g., [18, 45, 55, 68]), they only supported pointing interactions. In addition to the form factor of the surface, a touch sensing system should be installed in order to capture the user's precise on-screen input.

3. Arbitrary surface repositioning: To support various interactions in room-scale VRs, the surface should be automatically redirected and repositioned at arbitrary locations and angles in line with our assumption of a standing user. Reflecting the typical use of a drawing canvas, we assume that the movement degree of freedom should support three-axis movements (x, y, and z) and two rotations (yaw and pitch). We consider the surface's roll rotation (i.e., landscape to/from portrait) optional because the z-axis surface motion would be sufficient to create a vertically longer input space. Fig. 2 left summarizes the motion degree of freedoms required for the first UbiSurface prototype.

4. Explicit operation: Safety is our mandatory design concept. We installed basic safety mechanisms such as collision avoidance and emergency-stop systems. Unlike encounter-type prop repositioning systems [6, 28, 71] based on implicit user goal prediction, we operate the system based on explicit requests from users or predefined scenarios. For example, the user can call the robot touch surface only if they want it, or the system sends the robot touch surface to the virtual surface that is closest to the user (this method was utilized in the subsequently mentioned user study). This policy simplifies the system's workflow (e.g., eliminating the need for a prediction algorithm).

3.3 Implementation

3.3.1 Components. Fig. 2 right gives an overview of its configuration: a touch surface, motion tracker, lifting apparatus, and locomotion actuator. For the touch surface, we used a 32-inch PQLabs touchscreen with a lightweight infrared-based multi-touch surface. It is placed at the top of the robotic device, and to change its position, height, and orientation, we assembled a unique lifting apparatus that has a central lift actuator fixed inside the metal base unit with four rolling wheels. Two servo motors (Zorsky DS5160 High Torque Full Metal Digital Steering Servo) are installed at the top of the lift, and the touch surface is fixed on these servo motors, which allows adjusting

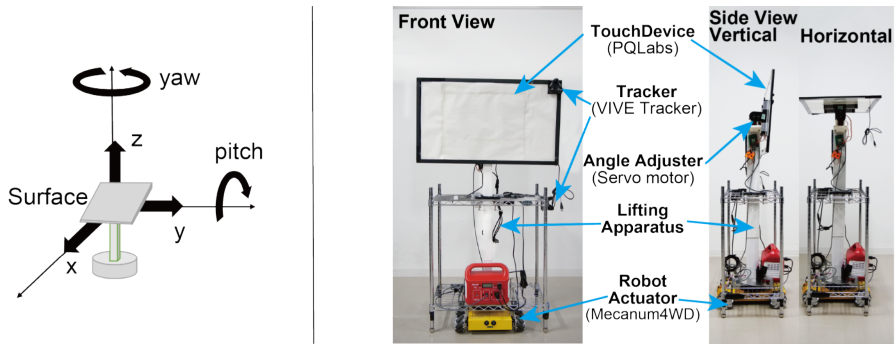

Fig. 2. The left side shows the dimensions of UbiSurface prototype. The right side shows the overview of UbiSurface prototype

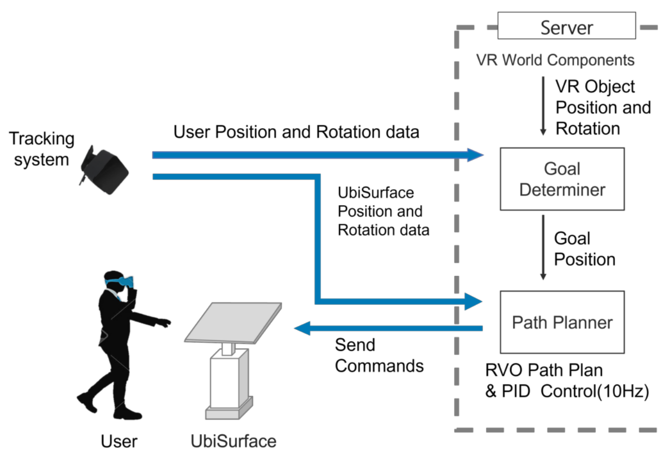

Fig. 3. System Overview of workflow

the pitch angle of the surface. To connect the components, we adopted a set of stable 3D-printed adjusters and holders. For the locomotion actuator, we used an omnidirectional mobile robot (Nexus Robot's 4 WD 100mm Mecanum Wheel Robot) fixed to the bottom of the base unit. This robot is wirelessly controlled via Bluetooth serial communication. The device has microcomputers and communication devices (ESP32) to drive it wirelessly based on the signals from the operating Windows server computer. A portable electric power station (SmartTap PowerArQ, 100V/2A) is mounted on the unit to supply adequate power to drive the lift actuator (59 W input) and other equipment (e.g., ESP32 board and VIVE tracker). Two HTC VIVE Tracker 3.0 trackers are fixed to the device, one on the surface and the other on the base unit, precisely monitor the system's current robot location and surface angle. With these actuators and communication devices, the touch surface's height, pitch angle, position, and yaw angle can be automatically adjusted.

3.3.2 Functionalities. With the current implementation, the pitch angle of the touch surface can be adjusted in the range of 0-180 degrees. The height can be changed from 0.85 m to 1.45 m. Here, 0.85 m is a suitable height when using the touch surface as a tabletop, while a height of 1.45 m simulates a vertical screen (i.e., whiteboard) for a standing user. The vertical elevation mechanism raises and lowers the touch surface at a speed of 0.035 m/s. The maximum movement speed of the omnidirectional mobile robot was kept to 0.4 m/s, which is slower than the walking speed of a HMD user in a virtual room (about 1 m/s [44]), but it is reasonable for safety considering the need to avoid collision between the user and the robotic touch surface. The weight of the entire device is about 18 kg.

3.4 System workflow

Fig. 3 shows an overview of the system workflow. The system is operated using a HTC VIVE VR tracking system, an HMD (HTC VIVE Pro), the proposed UbiSurface device, and a Windows server system. The server system runs a script to acquire the positions and orientations of the HMD and UbiSurface's VIVE trackers. When the HMD user initiates mid-air planar interactions or sends a request, the server acquires the position and angle of the virtual input surface. The Goal Determiner script then determines the goal of the UbiSurface device based on the given information. Next, the Path Planner script calculates the motion path of UbiSurface, where the RVO Path Plan algorithm [61] is employed to avoid any collision with the HMD user. Finally, the server manages UbiSurface's entire travel to the goal.

For the aforementioned UbiSurface control, we employed an explicit control mechanism where the user needs to push a button on the VR controller or gesture following predefined interaction templates. We used the predefined control in our subsequently mentioned user study.

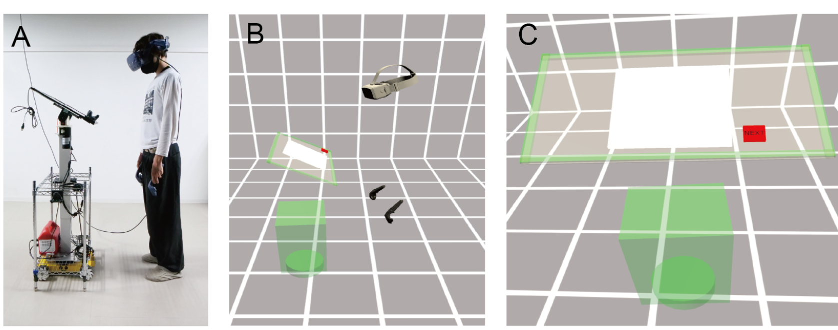

Fig. 4. Visualization of UbiSurface in VR. A: Side view in real space. B: Side view in virtual space. C: View from the HMD user.

3.5 Visualization of UbiSurface in VR

We incorporated suggestions from previous studies on robotic props (e.g., [28, 58, 71]) to mitigate user anxiety and increase safety by visualising the moving robots in the VR view, helping the user to anticipate when and how the robot is approaching. We introduced simple visualizations that show the physical surface and base unit locations of UbiSurface along with a white virtual canvas as shown in Fig. 4. This may reduce the effect of immersion, but that is not a priority in office use cases.

4 TECHNICAL EVALUATION

We run a brief technical evaluation to understand the basic performance of our prototype. We generated 25 goals with surface heights from 0.9 m to 1.4 m and angles from 0 to 180 degrees

Table 1. Errors for each parameter

Parameter	Average	Standard Division
Position [cm]	1.48	0.52
Yaw rotation [deg]	0.45	0.29
Height [cm]	1.78	0.95
Pitch rotation [deg]	0.34	0.34

Table 2. Speed of each actuator

Actuator	Average Speed	Minimum Speed	Maximum Speed
omnidirectional mobile robot [m/sec]	0.31	0.24	0.36
vertical elevation mechanism [m/sec]	0.031	0.030	0.033
surface angle adjuster [deg/sec]	23.2	22.9	23.6

Table 3. Technical evaluation of the prototype surface supporting force

Surface Angle [deg]	Center [N]	Corner [N]
0 (vertical)	25	25
30	45	30
60	100	47.5
90 (horizontal)	over 145	50

and randomly specified as targets in a 2.5 m × 3.5 m tracking area. Once the goal is specified in a simulator, the system immediately starts moving UbiSurface to it. We measured the four types of errors, position, yaw rotation, height and pitch rotation for the twenty-five trials. The mean and standard deviation of each error are summarized in Table 1.

Next, we examined the actual speed of each actuator in our current UbiSurface setup. we set 3.5 m travel, 0.9-1.4 m vertical elevation, and 0-180 degree rotation as targets for the ominidirectional mobile robot, vertical lift actuator, and pitch angle adjuster, respectively. We measured the actual working speeds 20 times for each actuator. Table 2 shows the overview of the results, which demonstrate the UbiSurface prototype with our workflow can mostly leverage the actuator's original capabilities.

Furthermore, we measured how much stiffness is supported by UbiSurface. We pressed the center and four corners of the surface in four different pitch angle conditions (full vertical, 30 degrees tilted, 60 degrees tilted, and horizontal) with a force gauge. Once the device itself is tilted, slipped, or the joint parts are bent, we stopped pressing and measured the force at the moment. Table3 summarizes the results. Because these stiffness data are strongly affected by the total weight of the base unit and the 3D printed angle adjuster's stiffness, we consider the current setup to be sufficient for supporting basic mid-air interactions, and it can be further customized with more weight or stronger hinges, especially for vertical and tilted conditions.

5 USER STUDY

5.1 Overview

A user study was conducted to investigate the effect of physical support by UbiSurface on the user's arm fatigue and input accuracy during mid-air interactions in a room-scale VR world. As a representative planar-input scenario, we designed two tasks: painting and writing. For both tasks, participants interact on a 2D virtual surface using a virtual writing tool operated via the VIVE handheld controller. We validated UbiSurface's performance by comparing it with a conventional mid-air method without physical support (Fig. 5). The study design below was officially approved by our university's Ethics Committee, including considerations for safety and prevention of COVID-19 infection.

We considered alternative baselines from the approaches of wearable, haptic device, and hand-held devices, but we could not find any suitable competitor. The most important condition for a meaningful direct comparison is that a canvas-sized planner surface be required. There is no suitable wearable force device that we can reproduce on our end. The available haptic devices (e.g., USB touch) have a very small input area for comparison. We have investigated whether a hand-held canvas-sized surface is comparable. However, such a surface is heavy and hard to balance with the single holding point, causing considerable fatigue to the non-dominant hand. Therefore, we decided to directly compare the UbiSurface and conventional mid-air input rather than making incomplete or unfair comparisons. Such a simplification of the study design also reflects our ethical considerations since the study attempts to simulate perceptual arm fatigue in our participants.

Based on fundamental prior knowledge, we formulated the following hypotheses.

H1. The UbiSurface condition is significantly less fatiguing during interaction than the mid-air condition.

H2. The UbiSurface condition is significantly more accurate than the mid-air condition.

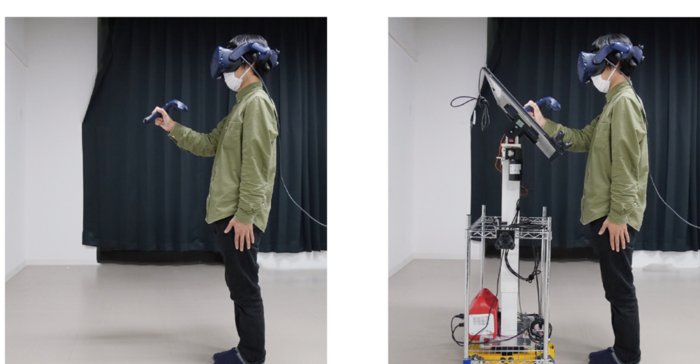

Fig. 5. Two interface conditions: mid-air input (left), UbiSurface (right)

5.2 Participants

We recruited 12 participants (age: 20-24 years old, 4 females and 8 males) from our university who have experienced VR headsets.

5.3 Apparatus

An HTC VIVE system was used for VR world rendering and spatial motion tracking. Fig. 6 shows the physical tracking area of around 2.5 m x 3.5 m, an HMD, and the UbiSurface device. We rendered a same-sized VR world using Unity engine. While a multi-touch surface is equipped on UbiSurface, we used the VIVE controller for both conditions as an input device for consistency between the conditions. This simplified the focus of this study: we examined the effect of physical surface support offered by UbiSurface (Fig. 5).

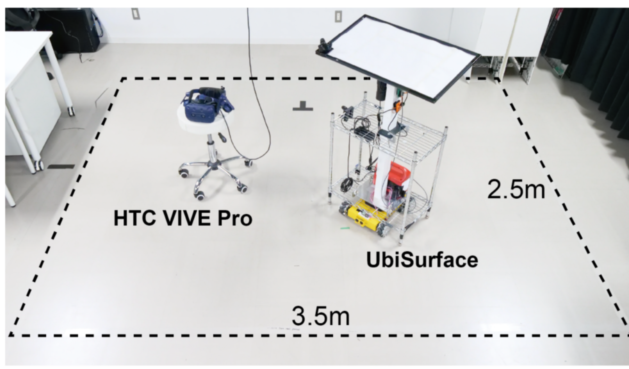

Fig. 6. Experimental space and apparatus

5.4 Task and Design

We designed the painting and writing tasks to examine prolonged mid-air planar interactions.

5.4.1 Painting Task. The painting task was to fill in shapes displayed on a virtual flat canvas, and it was designed to simulate VR users' arm fatigue during repetitive mid-air rubbing motions. Initially, a virtual canvas and a controller were displayed. Once participants approached it and clicked a button with the tip of the controller, an outer frame of a primitive shape (e.g., pentagon) appeared on the canvas. They were required to fill it in using a virtual brush as quickly as possible as shown in Fig. 7 (right). To induce consistent arm fatigue, we asked them to perform the task with only the dominant hand. When they completed filling in the shape and clicked the button near the canvas, the task was formally completed. Ten seconds later, another canvas appeared at a different location, and they repeated the same task with a different shape. Four different canvases were predefined around the users with different positions and angles, and only one of them was displayed during the task. As shown in Fig. 7 (left), the height and angle of the four canvases were 1 m and 90 degrees, 1.1 m and 60 degrees, 1.2 m and 30 degrees, and 1.3 m and fully vertical. Their locations were selected to reflect the UbiSurface's movement ranges and also to simulate a variety of mid-air interaction clusterings [9]. The 1.3-m vertical surface was mostly eye-level height, and it might have caused the heaviest upper-arm fatigue for our participant group (average height: 165.8 cm (152-178 cm)). Other conditions were expected to induce milder arm fatigue. This detailed design carefully induced apparent arm fatigue within the acceptable range based on our approved ethical application. To maintain their engagement, the shape and brush color were changed every trial. The painting area size (input area) was identical among all shapes.

The independent variable was input condition: UbiSurface or mid-air input. Each participant performed 3 repetitions for each canvas, which resulted in 12 trials per input condition. For the

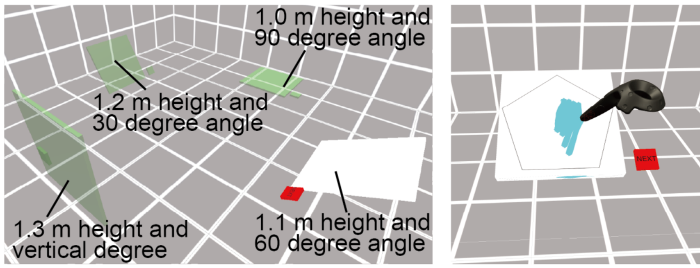

Fig. 7. Painting Task: (left) Overall view of virtual environment. Three green transparent canvases are initially invisible. (right) A participant paints the virtual canvas using the controller.

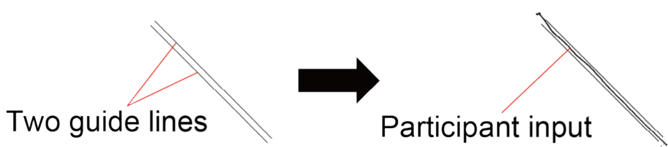

Fig. 8. Writing task. Two guide lines are presented initially, and a participant writes a new line along with the guides as accurately as possible.

UbiSurface condition, the physical surface was repositioned to the next canvas during the 10-sec break between trials. For the mid-air input condition, the arm and controllers were operated in the air. In both conditions, the participants could take a rest during the break time.

The dependent variables were the Borg CR10 physical exertion scale [10] (a famous metric of user's perceived arm exertion), NASA-TLX (subjective workload metric), and subjective feedback regarding preference and achievement on a 7-point likert scale. The Borg CR10 scale has been actively used for evaluating mid-air interaction workload (e.g., [15]).

5.4.2 Writing Task. The writing task was designed to simulate how a user can write precise characters or shapes in a VR space. As shown in Fig. 8, initially, two guide lines were given in the VR space (shown in Fig. 9), and participants were required to write a line between them as accurately as possible without collision with the guide lines. This study protocol was built based on common penmanship practice, and it is also traditionally well known as a steering task in the HCI domain [4]. Participants performed this writing task repeatedly on the horizontal and vertical virtual whiteboards, which is a typical example of a task causing heavy Gorilla arm issues [9]. The next guide lines appear once a trial is completed, and then the new trial begins. All trials were designed to have the same input difficulty with the same pen tip width (0.9 mm (3 px)), tracing length (176 mm (600 px)) and width (6 mm (20 px)) between the two guides.

The independent variable was identical to the painting task. We set two input conditions: UbiSurface and mid-air input. Participants repeated this writing task 36 times per input condition. The first 18 trials were performed on the vertical virtual whiteboard, and the other 18 trials were conducted on the horizontal one. Therefore, they completed 72 trials in total. The virtual whiteboards were physically rendered for the UbiSurface condition. From a pilot study, we observed slight

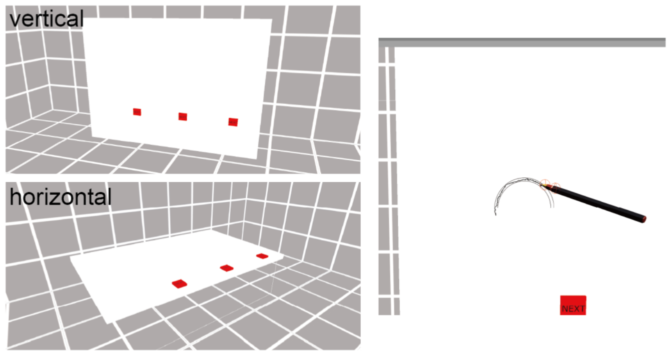

Fig. 9. Writing task. Two guide lines are presented initially, and the participant writes a new line along the guides as accurately as possible.

robot positioning errors that nevertheless affected writing quality as a result of the VIVE tracker's potential sensing errors. To compensate for such errors, the system automatically adjusted the virtual whiteboard position to match the arranged surface position of physical touch if significant errors occurred. Our dependent variables were identical to the previous painting task to capture the user's arm fatigue, and we additionally measured the number of collisions (counted when the user's writing line overlapped the initial guide lines) as a clear objective metric representing writing accuracy.

5.5 Procedure

Participants first signed a consent form and received an overview of the experiment. Next, they had a practice session before starting the main trial. The order of the painting and writing tasks were fixed: painting task, followed by the writing task, which reflected the difficulty of each task. The order of input methods (UbiSurface or mid-air) was counterbalanced, half of the participants started with the UbiSurface followed by the mid-air input, while the remaining half conducted the tasks in opposite order. A five-minute break was given between tasks. After each task, they responded to a questionnaire. An additional interview was also conducted after all tasks. The total duration of the study was about two hours per participant. They received payment of about 30 USD according to the university's regulations.

5.6 Result

Fig. 10 and Fig. 11 summarize the results of each task. A * in these graphs is a mark of significance detected by a Wilcoxon signed-rank test while applying the collected ordinary data.

5.6.1 Painting task. **CR10** Fig. 10 (a) shows the results of CR10 score in the painting task. The average fatigue of the dominant hand for UbiSurface was 25% lower than in the mid-air condition. This difference had a relatively large effect size (i.e., exceeding 0.5 [49]), but it was not significant ($p = 0.076, r = 0.513$).

Preference and Subjective Achievement Fig. 10 (b) shows preference and subjective achievement ("how well was the painting performed?") scores in the painting task. The average of preference score for UbiSurface was, significantly, 38% higher than in the mid-air condition ($p < 0.01, r = 0.744$).

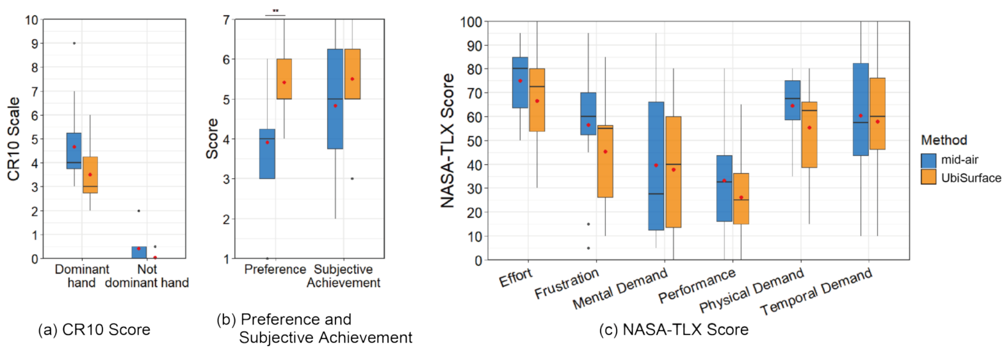

Fig. 10. Results of painting task. (**: $p < 0.01$, The red points show the mean of each data.)

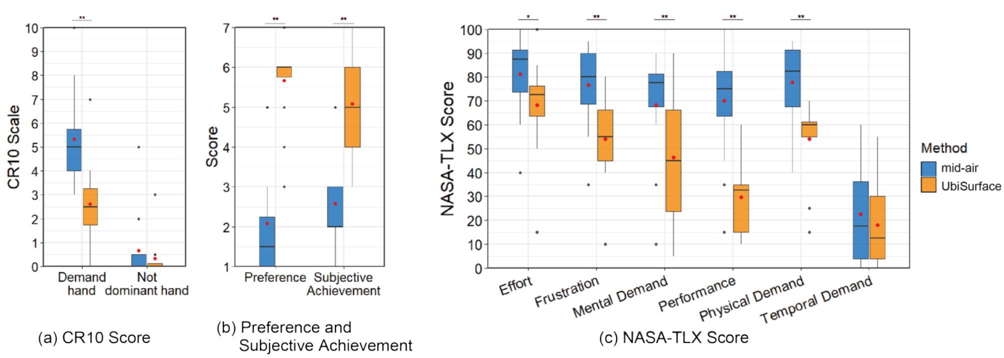

Fig. 11. Results of writing task (**: $p < 0.01$, *: $p < 0.05$, The red points show the mean of each data.)

The average subjective achievement score for UbiSurface was 13% higher than in the mid-air method, which was not significant ($p = 0.063, r = 0.537$).

NASA-TLX Fig. 10 (c) shows the results of all NASA-TLX question items. We did not find any significant difference between the UbiSurface and mid-air input conditions, although UbiSurface had relatively lower scores overall.

Therefore, our results did not support H1 in the painting task. We did not examine the metric corresponding to H2 in this task.

5.6.2 *Writing task.* **CR10** Fig. 11 (a) shows the results of CR10 score in writing tasks, demonstrating that the physical load of the user's dominant hand in the UbiSurface condition was significantly lower than in the mid-air input condition ($p < 0.01, r = 0.813$).

Preference and Subjective Achievement Fig. 11 (b) shows preference and subjective achievement scores. The average preference score in UbiSurface was 195% higher than in the mid-air input condition ($p < 0.01, r = 0.883$), and UbiSurface offered 117% higher subjective achievement than in the mid-air input condition ($p < 0.01, r = 0.883$).

NASA-TLX Fig. 11 (c) shows the results of all NASA-TLX questions. For all scores other than temporal demand, UbiSurface significantly outperformed the mid-air condition ($p < 0.01$, and

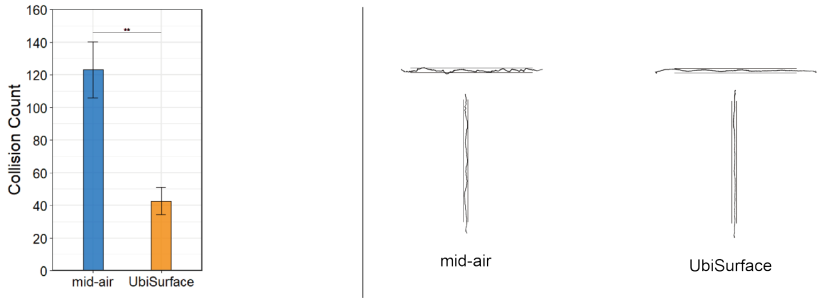

Fig. 12. The left side shows the number of collisions in task2 (**: $p < 0.01$). The bar charts show the mean with standard error. The right side shows examples of lines written by participants. The left side shows the lines using the mid-air method and the right shows the lines using the UbiSurface method.

$r > 0.7$ for all), suggesting our robotic physical surface significantly assisted the VR users' mid-air interactions.

Input accuracy Fig. 12 left shows the mean value of the number of collisions happened in the all writing task trials. The number of collisions with UbiSurface was significantly lower than in the mid-air input condition ($p < 0.01, r = 0.883$). Fig. 12 right illustrates representative examples of our participant's writing quality for both conditions, which also support this result.

Our results clearly supported H1 in the writing task based on the CR10 and NASA-TLX scores. Furthermore, the results of input accuracy clearly suggest that H2 is supported.

6 DISCUSSION

6.1 User study reflections

The system worked well throughout the study. We never observed collisions between the moving parts of UbiSurface and our participants.

The experimental results show that the preference score of UbiSurface was significantly higher than that of mid-air input for painting tasks. According to our post-trial interviews, participants preferred UbiSurface because the presence of the physical surface increased the realism of the painting activity, and it allowed them to easily adjust the brush's position and posture perpendicular to the canvas. However, we did not find significant improvement in reducing arm fatigue by UbiSurface in the CR10 scores, contrary to our expectations. Some participants felt that UbiSurface was easier because the correct reaction force from the surface was provided and fine-tuning of the pen's depth position was not required. Others, however, felt that the mid-air input was easy enough overall because they did not need to precisely adjust the brush tip on the canvas surface, since the painting was achieved even if the tip slightly penetrated the surface (i.e., the virtual tip is 5 mm long). This was our intentional setting to compensate for the error of the VIVE controller. As a result, they could still paint with rougher hand movements.

In the writing task, UbiSurface was more effective and successfully reduced arm fatigue while increasing overall performance. The post-trial interviews revealed that the hand position was easier to fix and more stably supported by the given physical support. Participants also commented that it was easy to keep the correctly tilted pen's posture (e.g., approximately 45 to 90 degrees) on the canvas with the UbiSurface touch device for both vertical and horizontal whiteboard conditions. On the other hand, the mid-air input condition did not help them to keep their correct pen's posture in the air, increasing their physical arm fatigue as well as mental stress. We acknowledge that the writing tasks were performed after the painting task, which means that potential and accumulated fatigue existed in the writing tasks. However, the difference between Ubisurface and mid-air input was sufficiently large, therefore we can still suggest that UbiSurface is effective for operations requiring high precision input and maintains correct penmanship postures with input tools relative to the input surface during handwriting tasks.

Reduced arm fatigue and higher input accuracy resulted from the presence of the physical surface; thus, we expect similar results to be obtained if physical props can be prepared and positioned for every trial. In other words, such primary benefit of passive haptics can be given to any virtual canvas without prior prop preparations when using the UbiSurface's motion capabilities.

6.2 Application examples and further customization

By simply adapting our experimental results, art studios, classrooms, design studios should be concrete applications where users can draw their sketches and paint freely around the studio. To an extent, office workspaces can also be rendered. For example, the horizontal touch surface can physically render a virtual software keyboard or digital tables. If UbiSurface's multi-touch surface is activated, typing will be the most practical scenario. One note for supporting text typing is that we still need more detailed finger position visualizations or real-time path-trough to let the users know which fingers are above each key. Another office-use case is book-end, where the touch action can be used for flipping pages and making annotations. Furthermore, UbiSurface would be useful for operating the control panels of virtual factories or laboratories (Fig. 13), where many control and input opportunities such as buttons and slide bars are enabled throughout the room to adjust the parameters of control and measurement units.

Fig. 13. Ubisurface helps the operation of controls such as push buttons or slide bars in a virtual plant.

Visualized data can generally be manipulated with navigation techniques. Specifically for life-size data visualization (e.g., airflow around a car or airborne virus spread), the scale information relative to the user's body, position, and room size should be maintained to understand the data scale and context correctly. In such cases, UbiSurface can help data analyzers or presenters to leave handwritten annotations in the spatial data within a life-size 3D scatter plot graph.

Another promising application of UbiSurface is as a test-bed for adaptive user interface design for XR users. For example, in recent years researchers have proposed toolkits to automatically design optimally personalized VR workspaces for individual users[19, 20]. For these toolkits, UbiSurface can be deployed as a physical tester to investigate how suitable a well designed ergonomic workspace is for dynamic contexts.

6.3 Safety

We never observed any physical contact with users while the robot was moving; however, we saw a few cases in which the participants accidentally kicked the stopped mobile robot. This is because the users often mistakenly estimated the distance between their own body and the UbiSurface body from the given spatial cues in VR view. One solution is improving the in-VR device visualization.

We could modify the visualizations by displaying the entire robot body and rendering the estimated user's foot positions. Such additional visual highlights in VR might scarify the user's immersive experience, but it is a necessary cost to maintain proper user spatial awareness and safe operations.

6.4 UbiSurface operation and deployment

We recommend using UbiSurface as a future accessory for room-scale VR with off-the-shelf VR headsets and controllers. The locomotion capability is useful not only for mid-air interactions. Only if participants think it is required do they need to invoke UbiSurface, which can be quickly and flexibly arranged at the currently working virtual surface. While not using VR applications, the enclosure of UbiSurface is unique yet offers conventional furniture functionalities such as moving ergonomic tables or flexible monitor stands. As discussed above, robots have been increasingly deployed in many places, such as homes, and offices, so our robotic device approach to supporting VR interactions could be well adapted to the near future infrastructure. Ubisurface uses a transparent panel as the input surface, which is well suited for AR or XR headsets and their applications because it does not occlude the in-VR or in-AR content [34].

7 LIMITATION AND FUTURE WORK

Positioning errors of robots significantly affect users' precise content manipulations. In cases where the physical surface is placed slightly above the virtual surface, users might not be able to touch the virtual surface. The biggest bottleneck is the accuracy of the motion-tracking system. The consumer-level VIVE tracking system has centimeter-level errors, depending on conditions. We suggest implementing automatic VR content adjustment so that it is always touchable or using a more professional motion tracking system with millimeter-level accuracy to minimize positioning errors.

Our findings were straightforward and confirmed our hypotheses well. However, the current study could not fully simulate the full user experience of UbiSurface, including waiting time and additional operation costs. For example, we moved the UbiSurface at break time during the study, however such operations might not be viable in more general dynamic scenarios. We acknowledge that our findings are limited to the fundamental effects of passive haptic with UbiSurface in a simplified room-scale VR context. Future work is necessary to test total user experience, including more technical and practical aspects such as time, user acceptance, a method to call the robot, etc.

The current surface size is practical but still not optimal. Considering use by a VR designer, the current canvas-size input surface might be smaller, and it should actually be the same size as a typical drafting table. One possible solution is using multiple UbiSurface units that operate under a swarm robotics algorithm [52, 57, 71], where two systems can be connected or separated to render different-sized virtual surfaces. Another solution to rendering a larger canvas is by slightly shifting the physical surface and mainly physically supporting the writing part, which might work when writing phrases in a sequential order. To make a surface more functional, it would also be beneficial to activate the multi-touch function of UbiSurface to support regular stylus inputs for thin-line drawing. Nevertheless, we should note that additional highly accurate finger or stylus tracking and in-VR visualizations are required.

8 CONCLUSION

We proposed UbiSurface, a robotic touch surface that can automatically reposition itself to physically represent a virtual planar input surface (VR whiteboard, VR canvas, etc.) and support users by providing accurate and fatigue-less input (handwriting, drawing, etc.) while walking around a virtual room. We designed and implemented a prototype of the robotic touch surface that could dynamically change a canvas-sized touch surface's position, height, and pitch and yaw angles to adapt to virtual surfaces spatially arranged at various locations and angles. We also evaluated UbiSuface's technical performances and effectiveness in mid-air painting and writing tasks. The results show that our system performed successfully and reduced arm fatigue while increasing input accuracy, especially for writing tasks. We discussed the results, alternative operations, and future deployment of robotic touch devises for room-scale VR systems.

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