IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 13, 2018, accepted November 12, 2018, date of publication November 28, 2018,
date of current version December 27, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2883821

Interacting Automultiscopic 3D With Haptic Paint Brush in Immersive Room

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This work was supported in part by "The Cross-Ministry Giga Korea Project" grant funded by the Korean Government (MSIT) (Development of Interactive and Realistic Massive Giga Content Technology) under Grant GK17C0100 and in part by the Technology Innovation Program (Development of a film-type transparent/stretchable 3D touch sensor/haptic actuator combined module and advanced UI/UX) funded by the Ministry of Trade, Industry & Energy (MOTIE, South Korea) under Grant 10077367.

ABSTRACT In this paper, we propose an interactive artwork system with automultiscopic 3D and haptic paint brush in an immersive room. Our system consists of a 81-view automultiscopic display, a handheld haptic paint brush, and a large-scale color palette station in a CAVE-like cubic room filled with the visual scene of the artwork. The 81-view rendering and multiplexing technology is applied by setting up the virtual cameras in the off-axis layout. The haptic paint brush is designed and implemented using a 2D array of multiple piezoelectric actuators. It provides the tactile feedback of spatial distance information between a virtual brush and a distal 3D object displayed on the automultiscopic display for the precise control of the brush when it is interacting with automultiscopic 3D. We demonstrate a proof-of-concept system that integrates a classic artwork into an innovative interactive system using novel multimedia and interactive technologies and evaluate our system using the handheld haptic brush for its performance and usability to enhance the user experiences.

INDEX TERMS Immersive environment, haptic feedback, automultiscopic 3D interaction, 3D haptic interaction, room-based VR.

I. INTRODUCTION

Recent advances in autostereoscopic and automultiscopic technology allow users to enjoy more realistic 3D without wearing dedicated 3D glasses. Such technology is beneficial for implementing interactive virtual environments since interaction and depth perception are two important factors that significantly improve the user experiences in immersive environment. However, there still exists a number of technical limits to orchestrate realistic 3D with viable interaction to achieve truly immersive, high fidelity environment including interaction with 3D to enhance the quality of 3D experiences, realtime rendering of multi-views, and user interface for natural human-computer interaction.

In this paper, we propose an interactive artwork system with an 81-view automultiscopic display and haptic paint brush in an immersive room where visual scene is projected onto each wall in the room. The aim of this work is to provide unique user experiences through 3D interaction with realistic 3D artwork using a haptic paint brush in a CAVE-like immersive room. Our proof-of-concept system transforms a classic artwork into realistic 3D media and enables users to explore the artwork while virtually painting it using the handheld haptic device, providing tactile information to the user's palm. This unique setup allows users to naturally engage in artwork painting with enhanced user experiences.

Our room-based system is filled with the artwork images using three projectors (one for each wall), and the 81-view automultiscopic display is placed at the center of the front wall. A handheld haptic brush is implemented for selecting the color from a palette station and painting the artwork. In this way, users can stand at the center of the palette station, select the color of their own, and paint the realistic 3D artwork through the brush with haptic feedback. Our system does not require any dedicated glasses nor wearable devices for visual

FIGURE 1. Ssireum artwork by Kim Hongdo from Joseon Dynasty of Korea. Image courtesy of Wikipedia [19].

and tactile experiences. Instead, we use automultiscopic display that naturally provides realistic 3D viewing experiences and haptic brush that facilitates more natural interaction with realistic 3D through tactile feedback. Orchestrating such system in a CAVE-like artwork room further provides immersive environment with reproduced scene of the artwork, allowing the users to experience and understand the work.

To demonstrate the feasibility of our system, we integrated one of the most famous classic artworks in Korean history called Ssireum (see Figure1). Ssireum means traditional Korean wrestling which gained widespread popularity during the Joseon Dynasty (A.D. 1392-1897) of Korea. We transformed this masterpiece into a state-of-the-art interactive artwork platform to share the idea of what painter wanted to deliver and provide the new user experience while enjoying the classic artwork. While the original artwork was painted with black ink only, we decided to allow users to paint the Ssireum characters with a wide selection of colors that users want so that they can enjoy and share the painting experiences while observing the artwork in detail.

The present study makes two key contributions. First, we demonstrate a system architecture that integrates 81-view automultiscopic artwork system with haptic paint brush in an immersive, room-based virtual environment. The completion of this work can provide the insights of how interactive and immersive system can be designed and implemented with realistic 3D contents. Second, we provide 3D interaction scheme that naturally provides haptic feedback information based on how the haptic brush is interacting with depth perceived 3D contents. This paper will be organized as follows. In Section II, related work is summarized. The overview of artwork painting room system is discussed in Section III. In Section IV, automultiscopic 3D visualization is discussed, followed by detailed descriptions of multiview display, rendering, and multiplexing. In what follows, we discuss 3D interaction with haptic feedback including haptic paint brush and haptic feedback system in Section V. Two user experiments are conducted and reported in Section VI. Finally, concluding remarks are drawn in Section VII.

II. RELATED WORK

A. ROOM-BASED VIRTUAL REALITY

The first room-based virtual reality, the CAVE (CAVE Automatic Virtual Environment) [4], was invented to provide fully immersive virtual reality experiences using four projectors in a room. In the CAVE, the three side walls are rear-projected and a floor is down-projected in a cubic room to visualize the virtual scene. When a participant enters the room and walks around the virtual world while wearing stereoscopic 3D glasses, the viewing experience is significantly enhanced so that the participant can feel more presence and is immersed into the virtual world due to dynamic changes of area surrounded. The Walt Disney adopted a projection-based augmented reality in Disney Theme Parks [7]. They built a projector camera toolbox to help create spatially augmented 3D world to enhance the theme park experiences. They have shown a number of successful installations such as *Cinderella's Castle* at the Magic Kingdom Park, *Storytellers Sandbox* at the D23 Expo, and *Snow White's Scary Adventures*. IllumiRoom [5] is an immersive, augmented system that augments the environment around traditional game content. It changes the appearance of the area surrounding a television by projecting the extension of game content while playing the main content through the television to enhance the viewing experiences. Since high resolution of main gaming content is displayed on the television and extended content is displayed outside of the television screen, the user can enjoy the game content with immersive gaming environment. RoomAlive [6] is a room-based augmented reality system that enables interactive projection mapping experiences to allow users to touch, shoot, and steer the projected scene that is co-existed with physical world. Beira *et al.* [8] developed a space augmented system for the stage for dance performance. Their system provides interaction between 3D geometry and perspective grids calculations with body movement. They designed three projection surfaces (left, right, and floor surfaces) which had an open angle of 90° between them. The motion tracking system was employed to capture the movement of dance performer. Based on the movement of dance performer, the geometric grid surroundings are dynamically changed to provide immersive environment.

B. AUTOMULTISCOPIC 3D DISPLAY

Autostereoscopic and automultiscopic displays are extensively studied with the advances of optical elements and computing power. The autostereoscopic display provides 3D illusion by binocular images without the need of any dedicated 3D glasses. The automultiscopic display extends this scheme by giving three or more views simultaneously and gives not only 3D depths but motion parallax either. The most common approaches to build optical set-ups for these types of displays include parallax barrier and lenticular lens. In parallax barrier method, an opaque layer with a set of linear barriers is attached onto the image source (such as LCD) which lets distinct sets of underlying pixels shown at different viewpoints to yield 3D illusion and motion parallax [9]. A number of recent studies focused on various aspects of parallax barriers. Lanman *et al.* [11] optimized dual-layer automultiscopic displays using low-rank light field factorization, increasing brightness and refresh rate of 3D display with parallax barriers. Efrat *et al.* [12] proposed a new display concept to support automultiscopic content in a wide cinema setting to accommodate multiple audiences with large scale automultiscopic display. Halle and Kropp [10] proposed a new rendering algorithm to rapidly generate images for full parallax spatial displays. Lyu *et al.* [14] proposed the use of a refractive medium between the display and parallax barriers to increase the potential viewing angle. Matusik and Pfister [13] implemented a scalable, 3D TV system for real-time acquisition, transmission, and multiview TV content with dynamic scenes. In this system, they used an array of cameras to obtain multiple perspective views of the scenes, and further developed a distributed architecture with a number of clusters to handle high computation and bandwidth demands.

In lenticular lens approach, an array of magnifying lenticular lenslets is attached onto the image source to provide different images to be directed into each eye. Woodgate and Harrold [15] designed autostereoscopic display that enables displays to be electrically switched between a full 2D and a half resolution autostereoscopic 3D mode. Takaki and Nago [16] presented a super multiview display with 256 different views using 16 LCD panels and 16 projection lenses. Takaki [17] also proposed a slanted subpixel arrangement for a flat-panel display using lenticular lens. In his slanted subpixel arrangement, it can prevent both crosstalk among the viewing zones and the angular-intensity variation in 3D images, enabling an increase in the number of views. More recently, Hwang *et al.* [18] proposed a local calibration method based on visual pattern analysis to improve the 3D visual quality for 3D lenticular display.

C. HAPTIC INTERACTION WITH HANDHELD DEVICES

Rantala *et al.* [1] studied the role of gesture types and spatial feedback in haptic interaction and evaluated three input gestures of moving, squeezing, and stroking to find out the appropriate methods for delivering haptic feedback using handheld device. They discovered that squeezing is the most suitable gesture for one handed interaction with the device. They also confirmed that multiple haptic actuators can allow more accurate gestures to define spatial patterns. Cha *et al.* [2] proposed a 3D video player system to provide haptic interaction with objects in a video scene using depth image information. In their system, audiences can explore the shape of objects using a PHANToM haptic interface. Kim *et al.* [3] employed handheld interface with haptic feedback for 3D interaction. Four infrared (IR) LEDs are installed in front of the controller for tracking the 3D position and orientation using the IR camera installed at the main system. The main system captures the IR LED markers through the camera and obtains the full 6 degree-of-freedom pose of the controller. The main system also collects the acceleration data and button state from the controller via Bluetooth. All the collected data is processed based on the continuous *HMM* (Hidden Markov Model) for gesture recognition. Dual mode of haptic feedback is provided using voice-coil actuator and vibration motor for richer haptic effects.

FIGURE 2. Artwork room.

III. ARTWORK PAINTING ROOM SYSTEM

This section describes how our artwork painting room system is designed and implemented. We also discuss the system pipeline and role of each component.

A. ROOM WITH PROJECTED VISUALIZATION AND AUTOMULTISCOPIC DISPLAY

Our system is installed inside a room where its walls are covered with the artwork using three projectors, one for each wall (see Figure 2, projectors are not seen in this figure). The size of room is 234 *cm* (width) × 400 *cm* (length), and the height of the room is 223 *cm*. Inside the room, a large-scale color palette station is placed for the color selection. A haptic brush is also installed next to the palette station. An 81-view automultiscopic display is embedded onto the front wall which is located in front of the palette station. A user is allowed to hold the brush from the palette station and start selecting the color and painting in the air while perceiving realistic 3D through the automultiscopic display in an immersive room. After completing the painting task, the artwork image projected onto the wall starts animating itself to enhance the user's visual experiences.

B. SYSTEM PIPELINE

The artwork painting room platform consists of *Main Server*, *Multi-view Rendering Server*, *Automultiscopic*

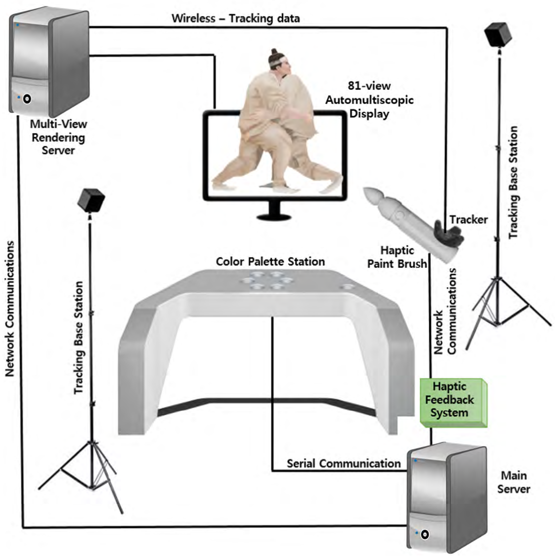

FIGURE 3. System pipeline.

Display, *Color Palette Station*, *Haptic Feedback System*, and *Haptic Paint Brush* (see Figure 3). In this subsection, we will discuss how each component is connected together and communicates with each other. We will also discuss the role of each server and entire pipeline in detail. We will, however, discuss more details about automultiscopic 3D visualization with multi-view rendering/multiplexing, and haptic interaction with paint brush and its feedback system in the later sections.

1) MAIN SERVER

A *Main Server* manages the entire system via network communication except for *Color Palette Station* which uses serial communication. For network communication protocol, we use UDP (User Datagram Protocol) to exchange the information among the servers and *Haptic Paint Brush* for realtime communication. Although UDP is a connectionless protocol, we were able to avoid any packet losses since the entire pipeline is communicated within a local network. We further adopt retransmission schemes for the critical packets. When the *Haptic Paint Brush* is inserted into one of the holes in a *Color Palette Station*, the *Color Palette Station* informs the *Main Server* in which color the brush is selected through serial communication. The *Main Server* then sends a packet to the *Haptic Paint Brush* to change its color LED to selected color and simultaneously sends the packets to the *Multi-view Rendering Server* to inform which color is selected. The *Main Server* is also responsible for controlling the projectors so that it runs animation when the user completes the painting.

2) MULTI-VIEW RENDERING SERVER

The *Multi-view Rendering Server* receives the tracking data from the tracker attached on the *Haptic Paint Brush*. It also receives the color selection information from the brush through the *Main Server*. We will discuss the details of how multi-view scenes are rendered in the later section. The *Multi-view Rendering Server* displays a virtual brush (that its movement is mapped in the screen in consistent with the movement of the real paint brush in a 3D space) in the screen to provide the visual cues to the user. The virtual brush paints the Ssireum characters with the color that has been selected at the *Color Palette Station* based on the brush movement. When the virtual brush is in contact to the surface of the Ssirum characters (when the brush makes collision with the character), the corresponding pixels are updated with the selected color. One of the noticeable features of the traditional Korean drawings is the spread of color pigment due to the capillary action along the paper fibres. To simulate this effect, we implemented a painting scheme such that pixel colors spread out when the virtual brush stays at a local region over a predefined time period.

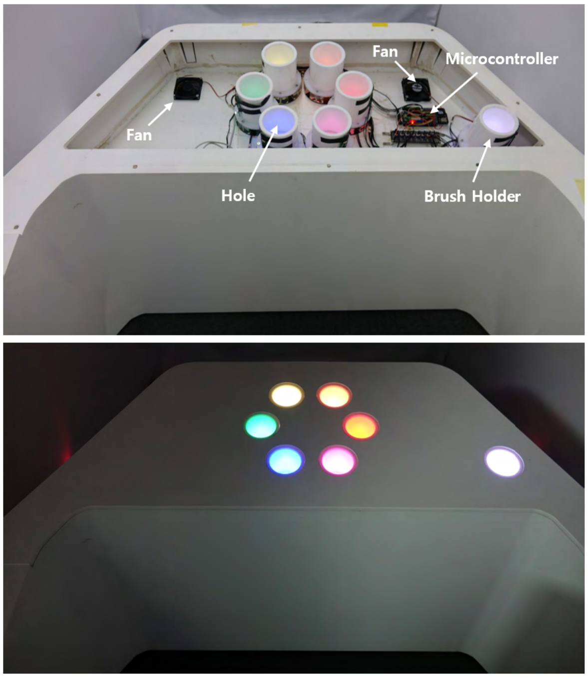

FIGURE 4. Color palette station. Without cover (top) and with cover (bottom).

3) COLOR PALETTE STATION

There are 7 holes (including one for the brush holder) with each hole is mapped with predefined color (i.e. red, orange, yellow, green, blue, pink, and black) in the *Color Palette Station* (see Figure 4. Please note that the brush holder is mapped with black color). Each hole is made of an acrylic cylinder with a magnetic sensor intact on top of a circuit board that is further connected with a microcontroller (ATmega328P, 16MHz, Arduino Uno, Arduino, Italy) in the *Color Palette Station*. When the *Haptic Paint Brush* is inserted into a hole, the magnetic sensor recognizes the neodymium magnets that are installed at the top of the brush body and notifies the *Main*

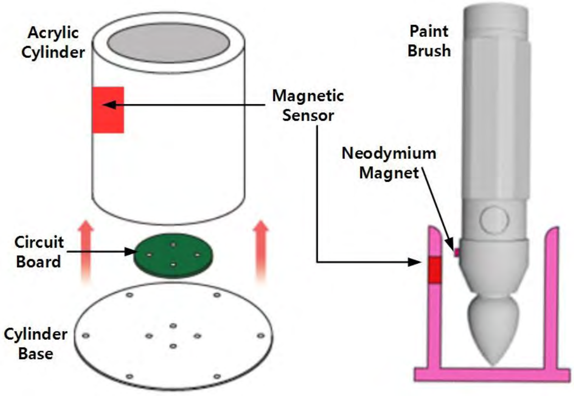

FIGURE 5. Structure of a hole in color palette station.

Server which hole the brush is inserted into (see Figure 5). The Gauss range of each magnetic sensor is appropriately adjusted to avoid any interferences between magnetic sensors.

4) HAPTIC PAINT BRUSH INTERACTION SYSTEM

A *Haptic Feedback System* is connected to the *Main Server* in order to generate haptic feedback signals and deliver them to 5 × 5 arrays of disc-type piezo actuators installed around the handle of brush. A Vive tracker is attached onto the brush in order to precisely track its position. This wireless tracker transmits tracking information to the *Multi-view Rendering Server* in order to render the virtual brush in a 3D space. When the tip of virtual brush collides with the Ssireum characters, the *Multi-view Rendering Server* updates the color of textures and notifies *Main Server* to control the *Haptic Feedback System* for generating appropriate haptic feedback signals. Details of haptic feedback interaction will be discussed in Section V.

IV. AUTOMULTISCOPIC 3D VISUALIZATION

A. AUTOMULTISCOPIC DISPLAY

We adopt an automultiscopic display to build a glasses-free, 3D volumetric canvas. On a 28-inch, 4K(3840×2160) LCD panel, a set of lenticular lenslets is attached which refracts light rays coming from each of the underlying RGB pixels into different angles. Consequently a user can see 81 disjoint sets of pixels along the horizontal direction, which provides 3D perception and motion parallax at the same time. It has an optimal viewing distance(OVD) of 1500 *mm* and the interval between adjacent viewing positions is 9.5 *mm*.

B. MULTI-VIEW RENDERING AND MULTIPLEXING

Visualizing multi-view images with an automultiscopic display usually consists of two stages: *multi-view rendering* and *pixel multiplexing*. In the multi-view rendering, images at all the 81 viewpoints are rendered in real-time to provide natural interaction between the user and the artwork content. Pixel multiplexing is a process to merge all the rendered images into a single 4K image which is appropriate to show per-view images along the viewpoints (Figure 6).

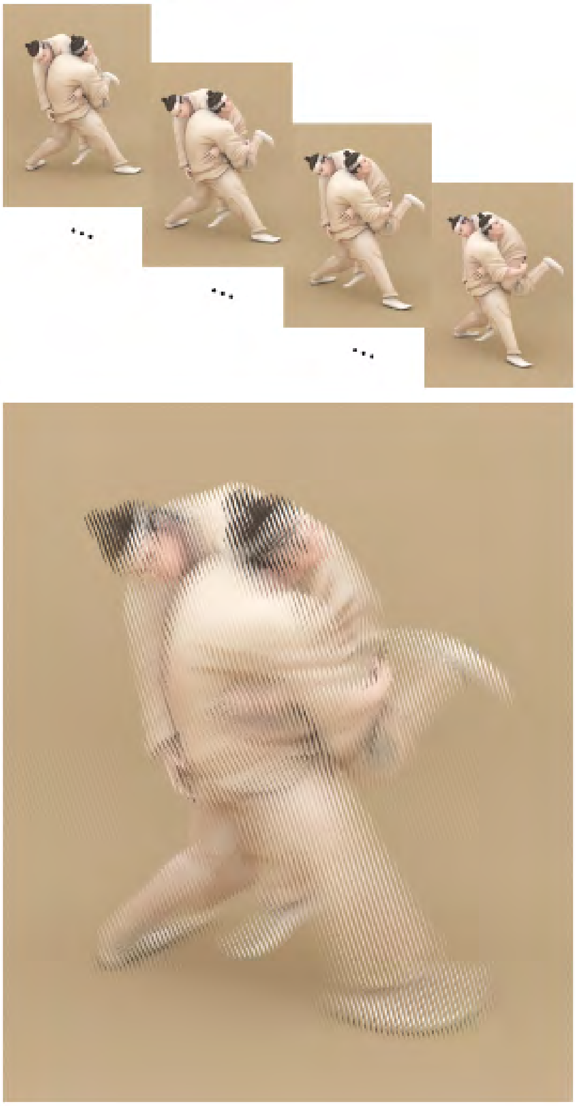

FIGURE 6. Source images (top) and their corresponding multiplexed image (bottom).

At the multi-view rendering stage, we utilize the Unity3D game engine as a real-time content generation platform. First, a set of virtual cameras is generated in the digital scene. To minimize image distortion and to improve stereo convergence, we use the off-axis scheme in which all the cameras are aligned in parallel and their view frustums are skewed to match the display panel. All the views are rendered into HD (1280×720) images and are tiled into a single chunk of texture memory (11520×6480) to minimize I/O overhead in the following processes.

The pixel multiplexing stage determines each of the RGB subpixels given the multi-view rendered images. Note that a single subpixel can be seen only along a very narrow angle due to the lenticular lenslets. So in this stage, what we need to do is to select a source view for each RGB subpixel according to the geometry of the lenticular lenslets and the pixel arrangement scheme of the LCD panel. Lenslets are slanted by arctan(1/9) in our display and the source view indices I_R, I_G, I_B of RGB subpixels at x-th column and y-th row are determined by:

$$\begin{aligned} I_R(x, y) &= (9x + y) \bmod 81 \\ I_G(x, y) &= (9x + y + 78) \bmod 81 \\ I_B(x, y) &= (9x + y + 75) \bmod 81. \end{aligned}$$

They can be independently calculated for each pixel, which is the kind of job such that the programmable GPU(Graphics Processing Unit) does very efficiently. We have implemented the pixel multiplexing with HLSL(High-Level Shading Language) and confirm that the whole visualization process runs over 70 FPS with a single nVidia GTX GeForce 1080Ti graphics card.

V. HAPTIC INTERACTION WITH HANDHELD BRUSH

We designed and implemented a handheld haptic paint brush for interacting with automultiscopic 3D objects. Our approach is to adopt spatial gesture of air painting by holding and moving the handheld brush in 3D direction with haptic feedback. Since the nature of automultiscopic display requires a certain viewer's distance between the display and the user's eyes in order to fully enjoy the glasses-free 3D content (2.5 *m* in our system), the paint brush with haptic feedback is a natural choice for our system. In this section, we discuss how haptic feedback system and haptic paint brush are designed and implemented, and how haptic feedback is provided when the user paints on a 3D object in the air.

A. HAPTIC PAINT BRUSH

The haptic paint brush consists of three parts: head, button, and handle (see Figure 7(a)). The brush head has a convex shape to articulate a paint brush bristle. We used semi-transparent plastic material for the brush head so that it can transmit the light from the color LED in the brush. The round button is located right above the handle so that it can be reached and pressed by a thumb when the user's hand is holding the handle of the brush. The shape of handle is a pentagonal cylinder and the handle itself is covered with rubber-like material. Inside the cover, the handle contains 5 × 5 piezoelectric (*piezo* for short) actuators in order to deliver haptic feedback to the user's palm. Details of haptic feedback will be discussed in the next subsection. The total height of brush is 280 *mm* and its inner circumference is 160 *mm*.

Inside the brush, a control circuit is placed in the middle. The circuit contains a micro-controller unit (STM32F407, Core : ARM Cortex-M4 processor with FPU, frequency up to 168 MHz, 210 DMIPS/1.25 DMIPS/MHz, and DSP instructions, STMicroelectronics, Switzerland), a color LED (LS5050RGB, Emitting color: RGB, China), an Ethernet network adapter, and a push button. The 5 × 5 piezo actuators were mounted on the outer surface of the handle of the brush (then covered with rubber-like material) and they are not part of the circuit board in the brush. Instead, the actuators are directly connected to the haptic feedback system. The micro-controller unit (MCU) controls all the components in the circuit board. The color LED is used to indicate which color the brush is using. The basic operation of the brush is that it continuously sends out the packets that contains time stamp and whether the button is pressed to the main server. The brush also receives a packet from the server regarding the selected color in order to change the color of the brush tip.

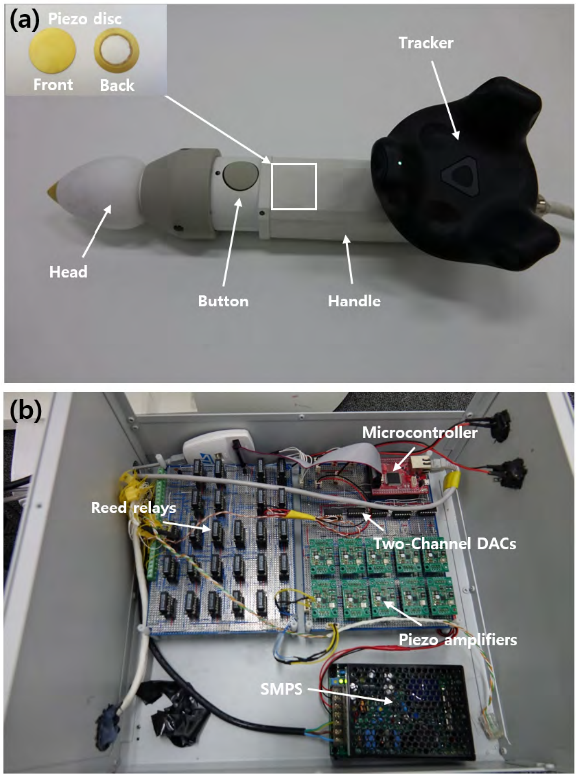

FIGURE 7. **(a) Haptic paint brush and (b) haptic feedback system.**

B. HAPTIC FEEDBACK SYSTEM

As shown in Figure 7(b), a haptic feedback system consists of a MCU (STM32F407), a two-channel DAC module (MCP 4902, Dual 8-bit Voltage Output DAC, Microchip Technology Inc, USA), piezo amplifiers (PDu100B, PiezoDrive, Australia), reed relays (DIP05-2A72-21D, Standex-Meder electronics, USA), and piezo discs (7BB-20-6, resonant frequency: 6.3kHz, capacitance: 10nF, plate size: 20 mm, element size: 14 mm, plate material: brass, Murata, Japan). As we mentioned in the earlier section, a 2D array of 5 × 5 piezo actuators are mounted around the handle of the brush and connected to this haptic feedback system. The rest of the components are implemented within the haptic feedback system.

The MCU contains haptic waveform pattern information. Based on the command packets received from the main server, MCU informs the DAC module through SPI to generate waveform signals based on the pattern information. The signals are converted into analog signals by the DAC module and delivered to the piezo amplifiers. Based on the operation mode (either row or column mode), the amplified signals are delivered to the piezo actuators via relays. When the brush is moving in a 3D space as if the users paint with the paint brush in the air, haptic feedback is generated on the actuators that are mounted around the handle of the brush. In this way, the users can feel the haptic feedback throughout their palm of the holding hand, providing the information of painted area that is mapped to the brush location in the 3D world coordinate. The brush can render different feelings by changing the amplitude, frequency, envelop, and duration of haptic feedback signal that is mapped to each row (or each column) of piezo actuators.

C. HAPTIC INTERACTION WITH AUTOMULTISCOPIC 3D

Depth perception and motion parallax are well visualized and presented using automultiscopic display as compared to ordinary display. However, it is difficult to precisely interact with a 3D object using a handheld device since the 3D object is displayed away from the user and thus visual cue of 3D depth is strictly limited, given the fact that it requires certain viewing distance to visualize automultiscopic contents. For this reason, we provide 3D depth information of an object through the brush with haptic feedback.

1) TACTILE PRE-CUE USING DISTANCE-TO-TACTILE CODING

Our haptic brush provides tactile pre-cue of spatial distance information between the virtual brush tip and a 3D object using distance-to-tactile coding when the tip is not collided with the 3D object. This tactile information is useful since the physical movement from the brush does not one on one match to the virtual brush in a virtual scene. Figure 8 shows how tactile information is provided based on direction of brush movement. In this figure, tactile feedback signals are delivered to one row at a time, from either *R1* to *R5* or vice versa depends on the movement direction of the brush. For example, if the brush is moving towards the virtual object, tactile feedback is repeatedly generated in a loop on *R1*, then *R2*, then *R3*, and so on. If the brush is moving away from the virtual object, tactile feedback is repeatedly generated in a loop on *R5*, then *R4*, then *R3*, and so on.

We apply a distance-to-tactile coding by controlling the transition time between the rows in accordance with the distance between the brush tip and the virtual object. For example, if the brush tip gets closer to the object, transition time becomes shorter. If the brush tip gets farther from the object, transition time becomes longer. In this way, the users recognize how close they hold the brush and which direction the brush is moving in reference to the virtual object. This haptic pre-cue that contains distance and movement direction information can be useful for interacting with automultiscopic 3D as it provides relative distance information between a virtual brush and a 3D object in a distal 3D space.

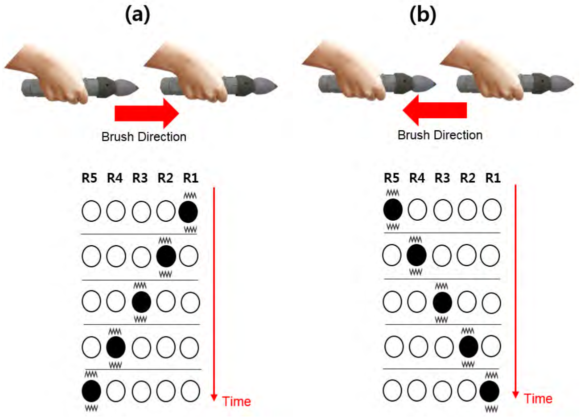

FIGURE 8. Haptic pre-cue of brush movement direction. (a) When a brush is moving towards an object and (b) when a brush is moving away from an object. Note that R1 is closer to the brush tip.

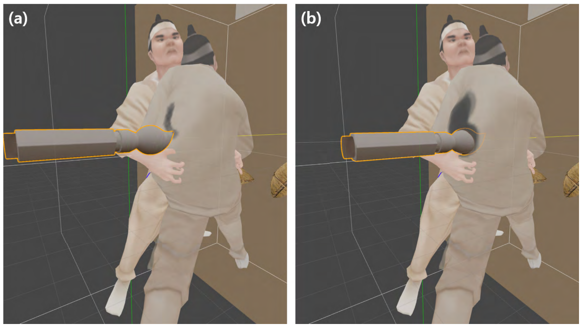

FIGURE 9. (a) Virtual brush is placed slightly over object surface and (b) virtual brush is placed deeply into the object.

2) AUTOMULTISCOPIC 3D INTERACTION WITH PRECISE CONTROL

We further provide distance information when the virtual brush makes contact with the object. This is simply achieved by providing distance information of how far the virtual brush is penetrated into the 3D object by providing different intensity levels. The distance between the virtual brush and 3D object is obtained whenever there is a collision, and is mapped into 5 intensity levels. Based on the intensity levels, we adjusted the amplitude of haptic feedback, so that the users can obtain how deep the brush is painting in regards to the object. When the brush tip is lightly painting onto the object, low amplitude of haptic feedback signal will be delivered along with the visual update of light painting (see Figure 9a). In contrast, when the brush tip is deeply painting onto the object, high amplitude of haptic feedback signal will be delivered with the visual update of deep painting (see Figure 9 b). In this way, users can paint the distal 3D objects with precise control with haptic information.

VI. EXPERIMENT 1

The goal of this experiment is to investigate the effects of haptic feedback when the paint brush is interacting with automultiscopic 3D with different depth perception. In this

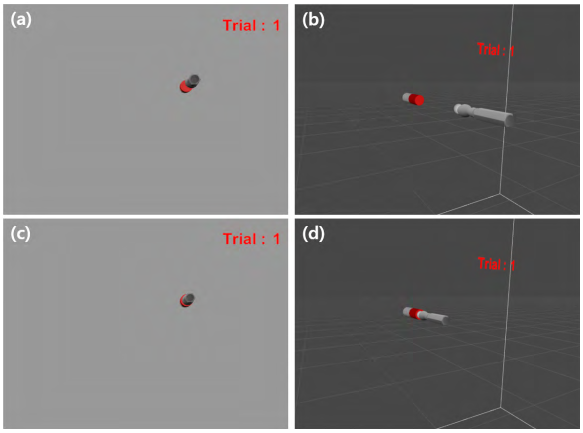

FIGURE 10. **Experimental application. A virtual brush tip is away from the red zone ((a) user's view and (b) perspective view) and a virtual brush tip is inserted into the red zone ((c) user's view and (d) perspective view).**

experiment, we particularly look into the benefits of using haptic feedback when the paint brush is spatially moved in mid-air in order to paint the virtual object that is visualized onto the automultiscopic display. In this context, we closely observe the feasibility of sensory substitution using haptic feedback since it is challenging to interact with distant 3D object with strong depth perception with handheld devices.

A. PARTICIPANTS

We recruited 10 participants (3 female; mean age = 29.1, SD = 3.9) in this experiment. They were all right-handed and all had normal visual and tactile sensory ability by self-report.

B. EXPERIMENTAL DESIGN AND CONDITIONS

Figure 10 shows an experimental setup using the haptic paint brush and automultiscopic display. A virtual paint brush is synchronized with a physical paint brush so that the virtual brush is moved in accordance with the physical movement of the actual brush in the air. The task is to insert the virtual paint brush into a red zone in the 3D cylinder-shaped target while holding a paint brush. When the brush tip is inserted into the red zone so that the brush tip is overlapped with the zone, the participants are required to press the brush button. If the brush tip is correctly inserted into the red zone, then the task is completed with a "success" message. If the tip is not correctly inserted into the red zone, then the participants are ask to repeat with a "fail" message. The task is continued until the tip is inserted into the red zone successfully. The task was built using Unity game engine (version 2018.1.1f1) [20].

A within-subjects experiment focusing on two feedback conditions was conducted: Visual Feedback (*V*) and Visuo-haptic Feedback (*VH*). In *V*, participants are asked to conduct the task without any haptic feedback from the brush. In *VH*, participants perceive strong and clear haptic feedback from the brush when they insert the brush into the red zone of cylindrical target. We provided predefined haptic feedback signal through out the entire handle of the brush when the brush tip is inserted into the cylindrical target.

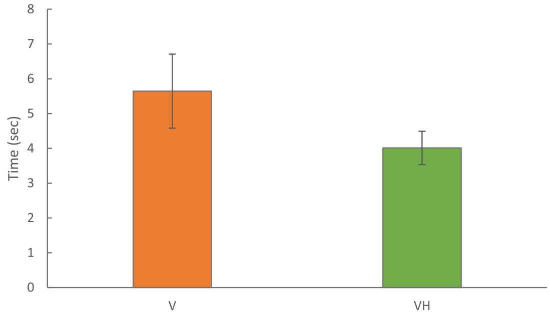

FIGURE 11. **Mean time to complete a trial.**

The depth size of cylinder-shaped target has three levels (i.e. low, mid, high) and the target with randomized depth size is appeared on the automultiscopic display. The target location was also randomized so that it was appeared in one of four different locations (i.e. *top+left*, *top+right*, *bottom+left*, *bottom+right*). Each session consists of 60 trials with combinations of three depth levels and four locations with one of two conditions. Participants are asked to complete 6 sessions (3 sessions for *V* and 3 sessions for *VH*), yielding 360 trials (60 × 6). Experimental conditions are also randomized among the sessions.

C. PROCEDURE

Participants are asked to hold the brush with their right hand and stand in front of the automultiscopic display. In each trial, participants are asked to move the brush to make its virtual brush pointing at a red sphere displayed on the center in the scene. The red sphere then turns into blue once the tip of brush is inserted into the sphere, and participants are allowed to start their task. As we mentioned earlier, their task is to insert the virtual paint brush into the red zone of cylindrical target and press the button as fast and accurately as possible.

After completing each trial, the experimental program recorded the task completion time T, the number of button press B, and the distance between the tip of brush and the center of the red area D. We asked participants to take a break for 3 minutes after each session to avoid any fatigue. The experiment took about an hour for each participant. A debriefing session also took place after the participants complete their experiment.

D. RESULTS AND DISCUSSION

All statistical analyses reported here were done using one-way ANOVA with repeated measures.

Fig. 11 shows the mean completion time T measured in this experiment. Average T was 5.64 seconds for V and 4.01 seconds for VH, showing people completed the task faster with haptic information. Statistical test revealed that feedback condition was a significant factor for T ($F_{1,9} = 5.63, p = 0.0417$).

Figure 12 shows the mean number of button presses B. Mean was 2.01 for V and 1.18 for VH. It is clearly observed

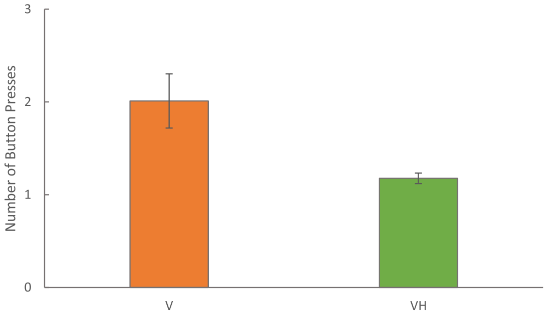

FIGURE 12. **Number of button press.**

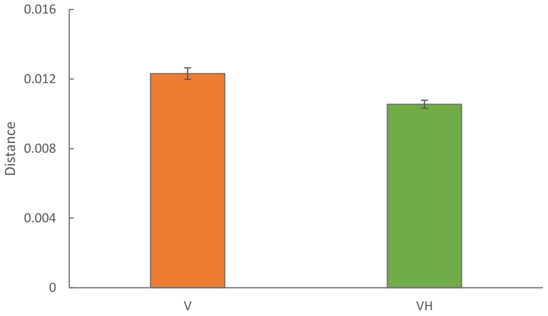

FIGURE 13. **Distance from centroid to brush tip location when button is pressed.**

in the data from Fig. 12. *VH* shows the benefit of using haptic feedback in addition to visual cues. Also feedback condition was statistically significant for B ($F_{1,9} = 10.56$, $p = 0.01$).

The mean distance D between the centroid of red zone and brush tip are shown in Fig. 13. Average distance was $2.75cm$ (1.23 unit in *Unity*) for V and $2.35cm$ (1.05 unit in *Unity*) for *VH*. It is also clearly observed that distance of *VH* is shorter than that of V, meaning that participants performed the task more accurately with haptic feedback. Statistical test confirmed that the feedback condition was a significant factor for D ($F_{1,9} = 0.0016$, $p = 0.0016$).

It is clearly shown that people performed better with *VH*. Participants completed the task faster, with less number of button press, and with closer distance to the centroid of target. This result implies that handheld interaction on automultiscopic 3D can be significantly enhanced with haptic information.

VII. EXPERIMENT 2

The goal of this experiment is to investigate and verify the feasibility and usability of haptic paint brush by comparing it with other types of computer interfaces when interacting with automultiscopic 3D in a room with immersive environment. We examined whether haptic paint brush brings better usability as compared to ordinary keyboard and mouse combination. We also compared the brush with a video game controller (PlayStation 2 controller).

A. PARTICIPANTS

We recruited another 12 participants (7 female; mean age = 28.5, SD = 3.7) in this experiment. They were all right-handed and all had normal visual and tactile ability by self report.

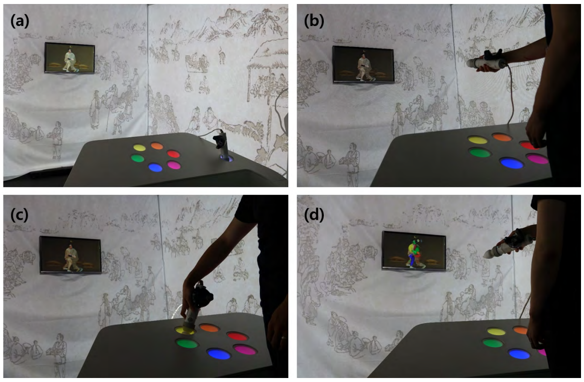

FIGURE 14. **Experiment setup for *H* condition. (a) Haptic brush is placed in a holder, (b) user is painting with the brush, (c) user is putting the brush into the hole for color selection, and (d) user is painting again with the new color.**

B. EXPERIMENTAL DESIGN AND CONDITIONS

In this experiment, we conducted a painting task with three conditions, each with different interface: Haptic Paint Brush (*H*), Keyboard+Mouse (*K*+*M*), and Game Controller (*G*). The painting task is designed to paint the Ssireum characters with a number of colors that they choose. In *H*, the virtual brush is synchronized with a physical haptic paint brush in 3D space. Selecting color is achieved by inserting the physical brush into the color hole in the palette station. In *K*+*M*, a virtual brush is manipulated in X-Y direction using the mouse cursor and Z direction using `UP` and `DOWN` keys in the keyboard. For coloring the character, `Left Click` in the mouse is used. A palette with seven different colors were located in the top-right in the scene and different color can be selected by using the mouse cursor. In *G*, the virtual brush is manipulated in X-Y direction using the left jog and in Z direction using the right jog. Similarly, coloring is activated when `O` button is pressed. For color selection, different color can be selected using the left jog and `O` button.

C. PROCEDURE

Participants are asked to enter the room and randomly assigned with one of the three interfaces (i.e. *H*, *K*+*M*, and *G*). Before starting the painting task, specific instruction is thoroughly provided by an experimenter to have a better understanding of using the interface. Once they receive the interface, they are allowed to freely use the interface to paint the Ssireum characters for three minutes. The task is repeated until all three interfaces were used.

After completing all three interfaces, a questionnaire is provided to participants to rate their experiences with each interface. The following 5 questions on horizontal lines with visual analog scale (with a label on each end: ‘Strongly Disagree’ and ‘Strongly Agree’) are provided [3]: *Easiness* - This interface is easy to paint; *Fun* - This interface is fun to use;

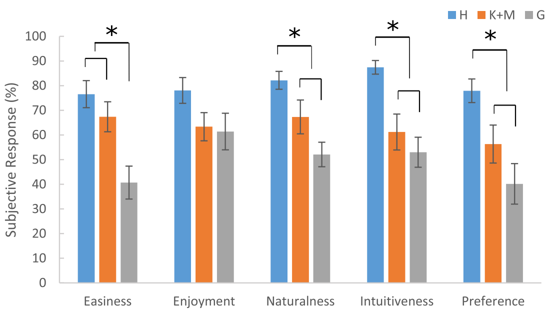

FIGURE 15. Subjective ratings. Statistical significance of differences between conditions were also represented by * ($p<0.05$).

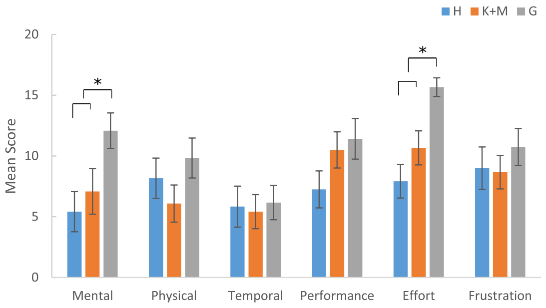

FIGURE 16. Mean TLX workload scores by condition. Bars represent standard error (*: $p<0.05$).

Naturalness - This interface is natural to use; *Intuitiveness* - This interface is intuitive to use; and *Preference* - I prefer to use this interface.

D. RESULTS AND DISCUSSION

Figure 15 shows subjective ratings of participants' continuous-scale for the five measures that are linearly scaled from 0 to 100 (0: Strongly Disagree, 100: Strongly Agree). In general, *H* had higher scores among the three conditions across the measures. An one-way ANOVA showed the significance ($p<0.05$) of interface conditions in *Easiness*, *Naturalness*, *Intuitiveness*, and *Preference*. Although, we could not find any significant results on *Enjoyment*, *H* had over 15% than *K+M* and *G*.

Student-Neuman-Keuls (SNK) comparison test was also conducted to show the differences between interface conditions. On *Easiness*, *H* and *K+M* conditions were significantly higher than *G* ($p<0.05$). On *Naturalness*, *Intuitiveness*, and *Preference*, *H* was significantly higher than other two conditions ($p<0.05$).

TLX data are shown in Figure 16. The results show that *H* condition was rated the lowest in *Mental*, *Performance*, and *Effort* and it was significantly lower than *G* in both *Mental* and *Effort* ($p<0.05$ for both).

In general, all the subjective measures (i.e. *Easiness*, *Enjoyment*, *Naturalness*, *Intuitiveness*, and *Preference*) are higher with *H* condition. This suggests that the usability and utility of haptic paint brush interface is remarkably useful when it is compared to conventional computer interfaces. It is clearly demonstrated that our haptic brush is easy, natural, and intuitive to use, and thus people prefer the brush over ordinary keyboard/mouse or game controller.

VIII. CONCLUSION

We presented an interactive artwork system with an 81-view automultiscopic 3D with haptic paint brush in an immersive room. The main goal is to demonstrate the feasibility of interactive artwork room system by integrating famous artwork into an immersive virtual environment. A haptic paint brush was introduced in order to provide haptic interaction with the 3D scene. We evaluated our system using the haptic brush and found that haptic feedback was useful in performance as well as its usability. We believe that the system architecture of our work can be beneficial for designing and implementing next generation virtual environment system for visual and tactile experiences.

ACKNOWLEDGMENT

The authors would like to thank D.-S. Choi, Korea University of Technology and Education, for his work on haptic feedback system and Y. Yoo, I. Joo, and H. Park of Vinyl-I for their work on the main server and color palette system. A 81-view lenticular type display is provided by the Korea Institute of Science and Technology (KIST).

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