AiRSculpt: A Wearable Augmented Reality 3D Sculpting System

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Abstract. In this paper, we present a new kind of wearable augmented reality (AR) 3D sculpting system called AiRSculpt in which users could directly translate their fluid finger movements in air into expressive sculptural forms and use hand gestures to navigate the interface. In AiRSculpt, as opposed to VR-based systems, users could quickly create and manipulate 3D virtual content directly with their bare hands in a real-world setting, and use both hands simultaneously in tandem or as separate tools to sculpt and manipulate their virtual creations. Our system uses a head-mounted display and a RGB-D head-mounted camera to detect the 3D location of hands and fingertips then render virtual content in calibration with real-world coordinates.

Keywords: Augmented reality, virtual sculpting, direct 3D manipulation, embodied interaction.

1 Introduction

With affordable consumer-level 3D printing there is more demand than ever for fast and intuitive tools for 3D modeling. Attempts to fill this gap have provided simplified adaptations of professional 3D modeling tools, but by duplicating the interaction design they do not contribute advances in fluid and intuitive interaction with what we are making. No matter how accustomed we have become to the 2D mouse and keyboard combination, it remains ill-suited to 3D spatial tasks of modeling.

We present a wearable AR 3D sculpting tool (AiRSculpt) that allows users to draw expressive sculptural forms in mid-air, transforming fingertips into scalable 3D brushes or erasers, and hands into gestural controllers, manipulating virtual content with bare hands like a lump of clay: melding the immediacy of freeform sketching and gesticulation with the exploratory craft of molding material into sculptural form.

A video-see-through head-mounted display (HMD) presents the real view augmented with sculptural content. An RGB-D head-mounted camera (HMC) detects hand and fingertip locations. Users thus communicate gestures to a camera that moves with them as an extension of their own bodies. They are able to see their hands, unencumbered by gloves or devices, directly interacting with their malleable sculptures within a real, personal environment; gaining an accurate sense of scale and depth with respect to their hands, and a preview of how a 3D-printed copy will appear in-context.

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Since the augmented space is fixed to real space coordinates, users can naturally shift their head to view what they are making from different positions and angles. Nevertheless, users retain advantages of virtual media including easy copying, scaling, and access to the object's interior. Transitioning between tools via gestures and finger postures interleaves more naturally with continuous sculpting than using menus. Selected tools and modal states are indicated by the color of augmented spheres at the fingertips. Gesture and posture design derives where possible from research on intuitive, natural hand gestures for spatial interaction and direct 3D manipulation [1, 2, 3, 4], and effective vision-based hand tracking and gesture recognition [5, 6].

The paper is organized as follows: Section 2 describes a user survey that confirmed the need for an easy-to-learn, intuitive 3D form-making interface with an interaction design divergent from existing systems, and compares our system to related works similar in spirit to our approach. Section 3 describes the system and interaction design, while Section 4 evaluates its effectiveness via an in-depth user study of a first prototype and a follow-up study of a second prototype. Section 5 draws conclusions from these results, suggesting potential applications and directions of further research.

2 Needs and Related Work

2.1 Preliminary Survey

We conducted a preliminary survey to ascertain demand for more intuitive alternative 3D modeling tools and to identify the demographic with the strongest need of this research. We gathered anonymized responses from 62 people (60% male, 40% female) from diverse backgrounds (53% science/engineering, 26% arts/design /humanities, 15% interdisciplinary). 80% of participants were in their 20s and 56% had experience using 3D modeling software. 82% said they enjoy sketching or doodling, and 84% chose pencil and paper as their preferred tool for quickly sketching out ideas. Although respondents were almost equally divided in whether they were satisfied with 3D sketching tools available today, those with prior 3D modeling experience formed 68% of the dissatisfied.

74% of respondents indicated that they have felt the need for a more intuitive modeling tool, again dominated by those with prior 3D modeling experience (constituting 91% of whom responded "definitely", 73% of whom answered "usually"). The circumstances in which this need was felt fell into five broad categories: when users get discouraged by the unintuitive interface (36%) and/or steep learning curve (20%) of existing systems, or find them inadequate for immediate or rough sketching (18%), or when they feel that drawing is difficult or not enough (15%), or desire an interaction more integrated with reality (10%).

People who expressed frustration with existing systems said they find it difficult to express the shape they want (especially smooth surfaces and natural, organic shapes), and time-consuming or painful to edit. Some explicitly stated a desire to experience their 3D virtual content in a real-world context and observe it from multiple angles. 63% of participants with 3D modeling experience did not find it comfortable to draw 3D objects with a mouse and keyboard, while only 20% did find it comfortable

(17% unsure). We observed similar results for whether it was easy to draw organic shapes using a computer (63% "no", 17% "yes", 20% "unsure").

The results of this survey clearly indicated that people from diverse backgrounds were overall dissatisfied with existing 3D modeling software options and felt strong needs for more intuitive and accessible interfaces. The people who felt this need the most were participants with 3D modeling experience. The majority (87%) were excited at the prospect of being able to draw directly in 3D space.

2.2 Related Work

Commercial digital sculpting software such as Autodesk® Mudbox®, Pixologic® Sculptris®, and ZBrush® offer an alternate approach to computer-based 3D form-making which incorporates physical sculpting techniques into the creative process. While they provide a more accessible, intuitive way of working than traditional 3D modeling tools, they are designed for a desktop environment typically accessed via a 2D interface. While some packages such as Geomagic® Freeform® are designed to work with haptic 3D input devices such as the Geomagic® Touch™, they remain generally confined to a 2D display that restricts its immersive capacity.

Most free-form 3D sketching or sculpting systems that had previously been implemented in a VR environment for 3D interaction research also utilize input devices, such as 6-axis spacemouse, sensors, physical props, or special VR gloves to track finger trajectory or hand movement [7, 8, 9, 10, 11, 12], permitting rich levels of interactive experience; however mediation via devices puts users at a visual and spatial remove from the virtual content.

Leap Motion's recent launch of Freeform, a free 3D sculpt application that allows users to create digital sculptures by manipulating a clay-like object with their fingers and hand gestures, shows industry advances made in the embodied interaction approach to 3D modeling. Although Leap's Freeform lets users sculpt with their bare hands, from the user's view their hands are physically removed from the site of creation, since it is not their hands but virtual representations of their fingertips as spheres that directly interact with virtual clay. With AiRSculpt, users can spontaneously create and manipulate virtual content directly in 3D with unencumbered hands. Also unlike Freeform, AiRSculpt is a HMD-based AR system that allows users to naturally explore and interact with virtual objects from various angles and distances within their personal environment. The benefits of moving to a 3D display for 3D modeling has been outlined well by Butterworth et al. in [13].

Many gesture-based modeling systems have also used physical input devices or wearable sensors. Gesture-controlled modeling systems such as methods using super-quadrics proposed by Yoshida et al. [14] and Nishino et al. [15], or Marshall's Virtual Sculpture system [1] are glove-based approaches focused on effective hand gesture mapping and control. AiRSculpt is driven by vision-based bare-handed interaction that uniquely integrates 3D free-hand input for 3D shape formation (Draw/Erase) with a gestural interface for tool transitioning and object manipulation (Scale/Rotate/Move). Attempts to use non-instrumented hand gestures for spatial interaction such as flying through terrain or composing a 3D scene in GestureVR [4], or basic 3D manipulation operations in Kolaric et al.'s Mixed Reality application [6] and Kim's Tangible 3D [3], are centered around mapping gestures to simple manipulation tasks such as selection and scaling and do not involve direct, expressive form-making operations like sculpting. Also unlike GestureVR and Tangible 3D, which use a VR platform, and Kolaric et al.'s application, which does not have depth occlusion, in AiRculpt users see virtual content within their real-world context and know where their hands are in relation to any virtual object, allowing them to naturally and fluidly interact with their virtual creations.

Our system uses a voxel-based sculpting method introduced by Galyean and Hughes [12], which mainly consists of an additive tool that adds material to 3D space like toothpaste being squeezed out of a tube and a subtractive tool that removes material. As far as we know, the volumetric sculpting approach has not been attempted in an AR environment with direct hand interaction.

3 Sculpting System

AiRSculpt is a 3D AR system in which users wear a video-see-through HMD with an attached RGB-D camera to create clay-like forms through bare-hand interactions.

3.1 System Modules

Tracking Modules. The software includes four tracking modules (hand tracking, gesture recognition, object detector, and coordinate calibration), a sculpting module, and a renderer (Fig. 1). The hand tracking module analyzes the HMC's depth image to derive 3D positions of hands and fingertips relative to the camera. The gesture

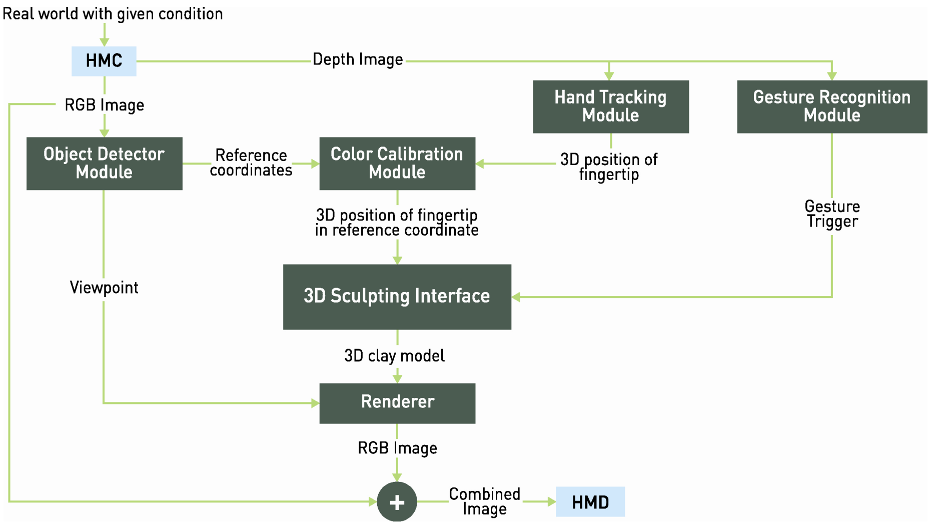

Fig. 1. High-level data-flow diagram of the AiRSculpt system

recognition module continuously analyzes the depth image to identify gestures by the user. The object detector analyzes the HMC's RGB image to detect a wall-mounted calibration image, using its reference coordinates to derive the position and orientation of the HMD. The coordinate calibration module combines hand-tracking and object-detection data to derive 3D hand and fingertip positions in reference coordinates.

3D Sculpting Module. The 3D hand and fingertip positions along with gestural input are used by the sculpting module to create, navigate, and manipulate malleable 3D virtual content (as described in section 3.2 below). We found voxel based geometry to be most suitable for freely generating and subtracting volume in 3D space, since it deals with the volume of the object directly [12, 16]. The volume is rendered as an isosurface via the marching cubes algorithm.

3.2 Sculpting Interface

The sculpting system operates between a system menu mode and a content creation mode. The system boots initially into the system menu mode, which can be used to start a new project, open an existing project, save, share, or print the current project, or exit the system. The menu consists of 2D buttons superimposed over the user's view, which are selected by moving their hand to the button's 2D position and making a grabbing gesture. Selecting the "New" button enters content creation mode, which starts with a clay-like ball by default. The system remains in creation mode until the target image is no longer in view; thus users can easily switch between modes by facing or turning away from the target image. This division rids the sculpting zone of bulky or intrusive menu interfaces and allows users to fully focus on creation.

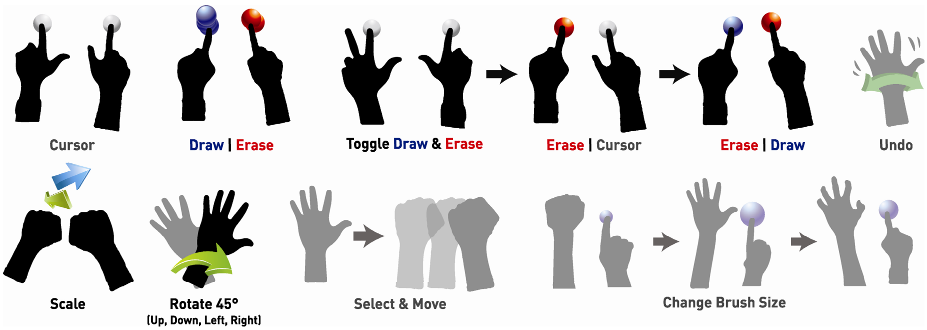

Fig. 2. The postures and gestures of AiRSculpt's editing and transformation tools

Within content creation mode, gestural controls allow seamless transitions between various functions without needing additional buttons (Fig 2.). Toward a more natural and intuitive way to interact with the augmented content, we drew inspiration from natural human behavior when manipulating real objects where possible. Nevertheless, due to difficulties of finger tracking with the depth camera we restricted the scope of the project to mainly utilizing the user's index fingers and thumbs; and due to limitations in the gesture recognition module, certain gestures (such as the gesture for toggling tools) appear unnatural.

Cursor. Opening the index finger and thumb in each hand activates the cursor function. Spheres augmented on the fingertips display the mode of each hand by color.

Draw/Erase. By touching thumb to index finger in one hand, Draw/Erase mode will be activated. If the hand is in Draw mode, the system will add volume along the trajectory of the index finger, with the shape of the selected brush and the thickness of its stroke. If the hand is in Erase mode, the system will remove volume along the trajectory of the index finger. When index finger and thumb are apart again, Draw/Erase mode is deactivated and the hand returns to cursor mode.

Toggle Draw/Erase. Opening three fingers triggers the switch between the two tools.

Brush Size Control. The brush size controls the amount of adding or erasing volume. The brush size function is activated when users move one hand to the upper-left corner of the screen. The system changes the brush size according to the degree of openness of the hand. Accessing the corner with a fist and gradually opening the fist increases brush size, whereas closing an open hand decreases it.

Select & Move. The user can select an object by making a grabbing gesture toward it with one hand. A selected object will follow the hand as long as the fingers remain closed, becoming anchored to the location at which the grip is released.

Scale. Users can activate the scale function by making two fists (and deactivate it by releasing them). While activated, the system scales the object in proportion to the distance between the two fists.

Rotate. A swiping gesture rotates the object 45 degrees in the direction the hand moves in (up, down, left, or right).

4 Experimental Results

4.1 Implementation

We used an Accupix mybud HMD, which supports 852x480 WVGA resolution and 35° diagonal FOV. For the RGB-D camera we used Creative Senz3D, which supports 1280x720 HD 720p RGB video, 320x240 QVGA IR depth video up to 30fps, and 74° FOV. We used Unity3D for software implementation, with the Intel® Perceptual Computing SDK 2013 R6 for hand/gesture recognition, and the Qualcomm® Vuforia™ SDK for image detection. At the time of evaluation, the brush size control, undo, select & move functions and the system menu mode were not yet implemented.

Fig. 3. AiRSculpt evaluation environment (left), and user's view at startup (right)

4.2 Evaluation Method

We selected six representatives of our target audience to participate in a small-scale, in-depth user study. The group included three males and three females, two from the arts, two from math and sciences and two from engineering backgrounds (four were also involved in interdisciplinary work). Half were experienced users of 3D modeling software (of which one had experience with virtual sculpting), while the other half had almost no 3D modeling experience at all. Two had experience in ceramic sculpture, and one was a media artist combining digital and physical media. None of the participants had experience using HMDs or VR/AR environments.

The evaluation of each participant was approximately an hour long and consisted of the following five different stages. First we gave an introduction to the gestural interface and had users practice gestural input and fingertip tracking with the Intel Perceptual Computing SDK Gesture Viewer (5 minutes), after which we gave a brief demo of AiRSculpt (3 minutes) and some practice time for the users to get familiar with its environment (5 minutes). Once the users felt ready, we gave them a series of tasks to be completed from simple to increasingly complex (10-15 minutes), and lastly when they finished we asked them to use AiRSculpt to create any form they please (15-20 minutes). Next we asked them to rate the difficulty level for all completed tasks and fill out a comprehensive questionnaire that combined sections from the most recent version of QUIS (Questionnaire for User Interaction Satisfaction) with elements from the standard USE (Usefulness, Satisfaction, and Ease of Use) Questionnaire. This was followed by a semi-structured interview assessing user experience.

The aim of this study was to gauge user reactions to our system, identify its strengths and weaknesses, and gain valuable quantitative and qualitative insight into how we could improve the experience, to better meet our objectives and expectations. All user tests were videotaped and interviews voice-recorded and transcribed with users' permission for subsequent analysis and documentation.

4.3 System and Task Performance

Users succeeded in accomplishing scaling tasks 100% of the time, having no trouble scaling an object up to twice its size or down to half or a third of its original size. Users also found it fairly easy to create a doughnut shape encircling the default ball,

	VERY HARD					VERY EASY
Depth Perception	1	2	2	0	0	1
Tool Transition	0	0	4	1	1	0
Scaling	0	0	1	1	4	0
Rotation	0	2	0	3	1	0
Rotation & Marking	0	1	2	3	0	0
Creating a donut	0	0	1	1	3	0
Creating a cone	1	2	2	0	0	0
Creating your own work	1	2	0	1	1	1

Fig. 4. Task difficulty assessment. Darker grid shading indicates higher frequency.

by either adding mass around the mid-point of the ball then rotating the ball until they came around full circle, or simply moving their fingertip 360 degrees around the ball. User performance was mixed when it came to rotation-centered tasks. Some users performed rotations effortlessly with great accuracy, whereas others only succeeded in getting the object to rotate half of the time at best. Rotations worked best when users made large, swift sweeping motions with their hands as close to their eyes (and camera) as possible. Most users improved rotations with time and guided practice.

Depth perception, i.e. determining the exact position of the virtual object relative to the user's hand, proved difficult for most users. Most often the virtual object was much further away from the hand than expected. Although users slowly improved in judging the relative distance with guidance and through trial and error, it remained a major source of frustration. Tool transition also took some getting used to, since the system had difficulty identifying how many fingers were extended. On average, users were able to transition from one tool another 7 out of 10 times throughout the evaluation process. Hand recognition worked best when the users placed their whole hand fully in view and their finger(s) extended enough to be distinguished from the palm of the hand. Consciously doing so disrupted instinctive natural interaction. Users found it challenging to make specific geometric shapes such as a cone or a pyramid, which took twice or three times as long as making a donut. Most users stated that AiRSculpt was not optimal for performing deliberate tasks of precision control; they found it much more enjoyable and satisfying to explore with task-free creativity.

4.4 Observations

All users quickly became adept at navigating the interface and transitioning between tools with gestures, and had a lot of fun playing and experimenting with the tool. Most users showed dramatic improvement over time through trial and error. Most also liked that they had a default clay ball to start out with.

Different users used AiRSculpt in surprisingly different ways. One person we evaluated moved around a lot to interact spatially with what she was making, busily viewing and changing things from different angles, even going down on her knees for a significant time to explore the interior, plunging deep into her virtual creation and reaching for things in a way not possible with a mouse and keyboard. Some users on the other hand preferred to stay relatively still, accessing different areas of the virtual object through rotation. Many preferred to sculpt standing, while some alternated between standing and sitting. However all users naturally moved toward the object for closer examination and away for an overall view.

Users also showed marked individual differences in how they used their fingers to draw or switch modes. One user tried to draw with her thumb instead of her index finger, and one user tried to use his pinky finger instead of his middle finger to transition between tools. One of the participants could not physically achieve a recognizable finger posture for toggling Draw/Erase. Some users preferred to draw with their palms facing toward them, while others facing away. The former had an easier time than the latter, since their hands were much less likely to suffer self-occlusion. Users primarily relied on visual feedback (change of colors) to discern state or selected tool, and hardly noticed the corresponding changes in text superposed on their hands.

4.5 Qualitative Evaluation Results

The qualitative evaluation was composed of a questionnaire and a semi-structured interview. The questionnaire was divided into five parts: 1) demographic; 2) overall user reaction; 3) system capabilities; 4) learnability (usefulness, ease of use, ease of learning, satisfaction); and 5) the top three positive and negative aspects of the experience. Parts 2, 3, and 4 used a 9-point rating scale. Questionnaire results showed the highest ratings for learnability, in ease of learning and satisfaction. All users easily remembered how to use it (8 point average), were able to accomplish tasks easily with few commands (7), and thought that steps to complete a task followed a logical sequence (7.2). Most users found it useful (6.9) and quickly became skillful with it (6.8). The poorest ratings were received for error correction and mistake recovery (4.5), since the prototype had no "undo" function. Users all enthusiastically agreed that AiRSculpt was fun to use (7.8), stimulating (7.5), and wonderful (7), but difficult overall (4.2).

Users most frequently used the words "fun" and "fast and easy to learn" in describing the most positive aspects of AiRSculpt. Some expressed appreciation for how well the head movement worked, and the two from the arts especially loved the bare-hand interaction. Other positive words users listed include "intuitive", "awe-inspiring", "chaotic", and "satisfying". Positive attributes they mentioned include easy tool transition, easy applicability, and conducive to creativity. In negative aspects, users most frequently mentioned discomfort of the HMD/HMC, with some expressing eye fatigue, unstable hand recognition interrupting the creative flow (by forcing the adoption of unnatural postures). Many pointed out the difficulty of judging depth, especially since our prototype did not use stereoscopic rendering nor depth occlusion of the see-through RGB video image. The only available depth cues were parallax due to head motion, and depth occlusion of the colored spheres on the user's fingertips.

The interview process helped us to contextualize the responses we observed and gain a deeper understanding of each user's experience with our system.

One particularly bold and exploratory user said she could probably "do this all day", even though she usually found it hard to be creative via computational means. She observed that AiRSculpt was apt for creating artistic work. Although she embraced the elements of unpredictability our system, some users found the lack of precise control frustrating, while others found it amusing but still wanted finer control. The media artist wanted fine-tuned control in the style of ZBrush (brush shape, type, size, material), but above all an "undo" capability. As an advanced user of 3D modeling software, he said that compatibility with other modeling software would be a critical factor in choosing a system. Another user indicated that the hardware quality and performance would be more decisive.

4.6 Preliminary Follow-Up User Study

We made several updates to our first prototype and conducted a short unstructured follow-up user study with this second prototype and four of the six participants from the former study. One significant change to address users' depth cue issues was the addition of depth occlusion by the hands over the virtual content, such that hands can appear in front of or behind parts of the virtual object according to the relative depth. Another change was the addition of a 2D button in the right-hand corner of the interface as an alternate method to toggle the Draw/Erase tools (triggered by 3D collision test), to address the difficulties some users found with the gesture-based trigger. The button also reflected the active tool by color. Other adjustments included making the initial size of the clay ball smaller to extend the available space of play, and using a more realistic clay-like rendering. The primary interests of the follow-up study was whether the added depth occlusion resolved previous perceptual errors, and whether any changes had meaningful impact on the quality of the user experience.

All participants agreed that depth occlusion was a major improvement that made AiRSculpt significantly easier and more intuitive to use. Although other parts of the system were unchanged, users perceived it as more robust and reliable. They felt that they had more control over what they were doing, allowing them to work much faster and be more ambitious with their creations than before, which made the process of making more immersive and satisfying. We were surprised at participants' skill-retention from the last experiment two months prior; most were immediately familiar with the gestural interface and hardly needed re-training or guidance. Only one participant clearly preferred the touch button over gestural input for toggling Draw/Erase, but all thought having both options was positive. All participants relied on the color of the augmented fingertip sphere to identify the active tool, and found the additional color cue of the button unnecessary. Users reported that having a bigger canvas to work with gave them a greater creative scope. Most preferred the smoother more clay-like texture, but some requested the option of choosing different kinds of materials. Criticisms centered on the discomfort of the glasses, and the distracting way they let in ambient light at the sides. The system had difficulty recognizing the smaller-than-average hands of one user. Users experienced difficulties due to the limited rotation options and range of scale; it was easier to physically move to view the object from a desired angle. Many users expressed that need for brush size control is essential for finer detail and expressive potential.

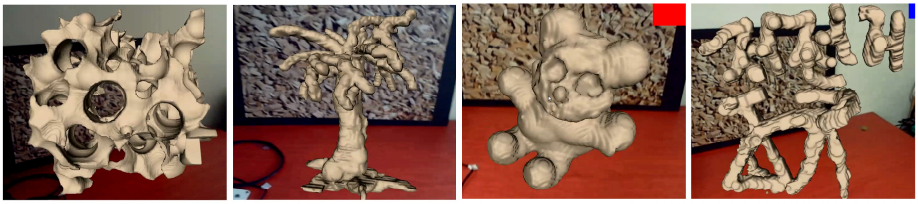

Fig. 5. User creations made with the second prototype

5 Conclusions and Future Work

Preliminary evaluation results confirm that AiRSculpt is fun, playful, intuitive, quick to learn, and a stimulating tool that encourages creative exploration and experimentation, especially suitable for artistic work. The element of play proved to be a significant factor that appealed to all users, and everyone agreed that the 3D interface and bare hand interaction made the experience of making more intuitive, immersive and satisfying. Remaining frustrating aspects derived from unreliable hand and gesture recognition and the uncomfortable or nauseating head-mounted hardware. All participants agreed robustness would dramatically increase the creative potential. Surprisingly, only one of six users observed the lack of tactile or haptic feedback.

We were encouraged by the detailed feedback we received from our participants, and are eager to forge ahead with intuitive interaction design for 3D virtual sculpting via HMD. What we seek is something not only fun and engaging, but also creatively liberating and useful. AiRSculpt seeks to seamlessly integrate the virtual realm with our physical environment as if one were a natural extension of the other: using AR technology to sculpt beyond the screen through natural bare-hand gestures. We want to provide users with the ability to create virtual matter anywhere within a more expansive sculpting zone, as opposed to being limited to manipulating pre-existing mass. It will be useful to give users the freedom of setting custom gestures for certain functions. We plan to move onto a stereoscopic view for enhanced immersion and depth perception. A comprehensive user study on a bigger scale will also be conducted to further improve our system.

Potential Applications. Interesting potentials of a portable AR sculpting system include the ability to prototype and compare 3D forms within a user's desired physical setting before fabrication, and collaborative working within a shared physical space or remote locations. We also envisage potential use for creative empowerment in arts education and art therapy.

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