Incorporating Kinesthetic Creativity and Gestural Play into Immersive Modeling

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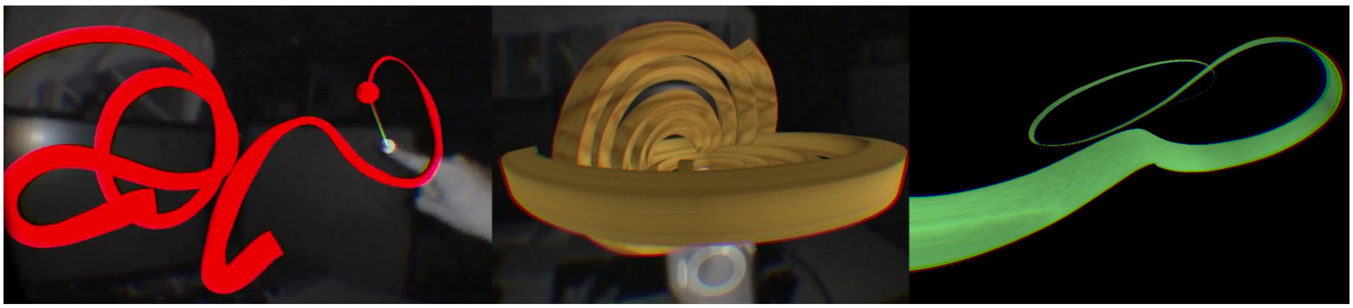

Figure 1: (Left): Spring-mass brush in velocity mode. Variations in stroke weight reflect velocity changes. (Center): Experiments in shape-making with the spring-mass brush. (Right): Variations in curvatures achieved by adjusting the spring's dynamic settings.

ABSTRACT

The 3D modeling methods and approach presented in this paper attempt to bring the richness and spontaneity of human kinesthetic interaction in the physical world to the process of shaping digital form, by exploring playfully creative interaction techniques that augment gestural movement. The principal contribution of our research is a novel dynamics-driven approach for immersive freeform modeling, which extends our physical reach and supports new forms of expression. In this paper we examine three augmentations of freehand 3D interaction that are inspired by the dynamics of physical phenomena. These are experienced via immersive augmented reality to intensify the virtual physicality and heighten the sense of creative empowerment.

CCS CONCEPTS

• **Human-centered computing → Gestural input**; *Interaction design*; *Virtual reality*; *Mixed / augmented reality*;

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KEYWORDS

Embodied interaction; kinesthetic interaction; gestural augmentation; immersive modeling; 3D modeling; 3D user interface; augmented reality

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1 INTRODUCTION

Myron Krueger, a computer artist and pioneer in virtual reality (VR) interaction, argued that the real power of VR is not in its capacity of illusion, but in its potential to extend our physical reach; and what is critical in constituting "reality" to our perception is the "degree of physical involvement" [28]. In the same spirit, our research utilizes immersive technologies, continuous gesture capture, and physically-inspired simulation to extend our bodily powers into the creation of virtual sculptural forms that would be near impossible to achieve in the physical world.

The main contribution is a new dynamics-driven approach for immersive modeling, bringing to HMD-based VR an enrichment of creative processes afforded "gestural augmentation" inspired by physical simulations [16]. The dynamic models that virtually augment gesture in this research are physically inspired yet under the creative control we exert over and through our own bodies. The interaction is designed to incorporate sophisticated movements on an intimate scale – the fine-tuned physical control we can exert using our hands and fingers – in tandem with the intuitions we have of the physical dynamics of familiar materials and objects. The focus here is on expressive capacity supporting creative processes, rather than efficiently or effectively obtaining a specific output. VR and augmented reality (AR) technologies are primarily utilized as a means of embodied interaction that expands our own creative capacities. The ultimate goal is to effectively extend our physical reach and support new forms of expression; to dexterously create visually expressive forms that would be arduous to achieve otherwise, all through playful experimentation.

2 RELATED WORK

2.1 Augmented Gestural Strokes

In 1989 Paul Haeberli developed a "dynamic drawing technique" for his 2D drawing program *Dynadraw* [8]. He re-imagined the brush as being a physical mass that was attached to the mouse position by a damped spring and tugged around whenever the mouse moved, instead of being at the exact point of the mouse itself. By augmenting gestural strokes with a spring-mass simulation, *Dynadraw* creates expressive strokes that amplify the qualities of the gesture. Scott Snibbe's *Dynasculpt* [25] was directly inspired by *Dynadraw* and attempted to use its drawing method to draw in 3D. Our approach expands upon Snibbe's exploration of novel opportunities afforded by the use of physically inspired dynamic models unconstrained by real-world laws. The interaction design of our system also uses physical simulation to enrich the dynamic between the user and the system and thus expand the expressive capacities of gestural movement. Unlike *Dynasculpt*, our spring-mass prototype has users directly steer the mass with the unfiltered movement of their fingers, and their drawings materialize directly where they perceive the mass to be, augmented within their own physical space. Head movements naturally correspond with changes of view of the emerging sculptural form. With the removal of these perceptual barriers, we theorize that users would not show a "tendency to draw in planes" [25] as with *Dynasculpt*.

2.2 Gestural 3D Modeling

A detailed introduction to early graphics research in using sweeping 3D input for modeling can be found in [14], which outlines the substantial advantages of using a stereoscopic or immersive display for anything from simple CAD-style manipulations to the complex operations of freeform extrusion.

Most recent freeform modeling approaches that incorporate sweeping 3D input belong to two broad categories: those that rely on the in-air movements of a tracked device, and those that employ haptic mediation to enhance control over input or mimic tactile interactions with clay-like substances in physical reality [11].

Surface Drawing [23] used glove-based input in a semi-immersive environment and used sweeping movements of the hand to generate a surface. One of its biggest drawbacks was having to use a custom-made data glove with a tabletop VR device. CavePainting [12], a full-featured 3D painting medium for artists and designers, allowed users to create 3D brushstrokes with physical props within an immersive CAVE environment. While Cave-Painting worked well as a new art medium that allowed artists to paint in 3D space, its aesthetics and interactivity remained generally tethered to emulating a 2D medium in its painterly style and method of mark-making. It also required a highly specialized environment with expensive equipment (the CAVE itself). While Surface Drawing and CavePainting were both successful in demonstrating the potential application of direct, gestural 3D input for art and design, they were dependent on custom-made devices and used immobile platforms that were fixed to a physical device or environment. Their methods were also focused on visualizing the gestural stroke as accurately as possible and refrained from using any form of gestural augmentation. Mäkelä's experiments with the Näprä prototype [17–19] proposed a slightly different and more delicate approach to 3D mark making. Näprä–a wearable mechanic device for both hands that wraps around the fingers–is designed to track the fine and subtle movements of the fingertips for fuller expression and interaction in a CAVE-like immersive environment [22]. Her findings suggest that real-time fingertip interaction allows for fine control and intuitive command, and works especially well for two-handed tasks that require both hands to work simultaneously in different capacities. While the prototype presented in this paper relies solely on vision-based fingertip tracking, its interface is also built around the expressive potential and control capacity of our fingertips.

2.3 Immersive Painting and Sculpting Systems

The substantial advantages of an immersive modeling environment, especially the benefits of using our spatial intuitions to create and manipulate virtual models, have been confirmed and discussed in numerous studies [1, 4–7, 9, 10, 17–19, 24, 30]. The potential of immersive technologies for supporting the early stages of the creative process in design practices is methodically explored in [1, 9, 10, 30]. Many concrete potential advantages of immersive 3D sketching for creative design, such as being able to sketch life-size models in proportion to our bodies and observe their spatial impact in the process, were identified through empirical studies and expert discussions [10, 30]. A recent in-depth user study conducted over a two-week period [9] showed that it was possible for designers to develop their own unique creative strategies of gaining a degree of mastery in handling digital substance, in the absence of material constraints in an immersive modeling environment. [20] and [26] exemplify recent research endeavors to integrate immersive interaction techniques into existing 3D modeling software, specifically Blender and SketchUp, to combine the effectiveness of spatial interaction with the powerful capacities of established full-featured modeling tools. These experiments in VR adaptations, however, are only in its preliminary stages and have been limited to simple manipulation tasks that do not involve freeform gestural input.

Rapid technological advances in VR and AR are fueling the development of new immersive modeling software for emerging head-mounted display (HMD) platforms such as the HTC Vive and Oculus Rift. VRClay [29] is a 3D sculpting software made for the Rift that supports two-handed interaction with Razer Hydra controllers. With VRClay users can enjoy the powers of digital sculpting directly in 3D, with one hand controlling the model while the other sculpts. Tilt Brush [27] is also a VR HMD application that allows users to paint with on 2D planes that could be moved and rotated in 3D space to create 3D paintings. Graffiti 3D [13], which allows users to draw directly in 3D with their fingers in AR with a Leap

Motion sensor mounted onto the Oculus Rift, was developed using the same Leap Motion VR platform that was used to build our prototype system. All the immersive drawing and sculpting tools mentioned above capitalize on the affordances of an immersive environment to provide a novel and more intuitive experience of creating 3D virtual content that is liberated from the rigid confines of a 2D static monitor. None of them however incorporate dynamic models to augment gestural expression.

3 SYSTEM DESIGN

The system presents three different physically inspired augmentations of freehand 3D gesture, within an HMD-based VR or see-through AR immersive experience.

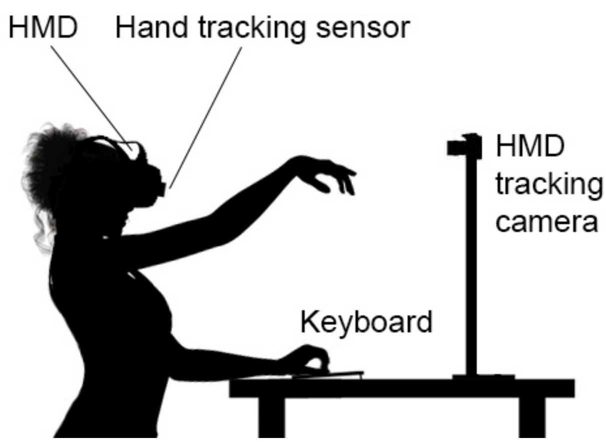

Figure 2: The working environment.

3.1 Hardware and working environment

The system's hardware consists of a VR HMD (Oculus Rift Development Kit v.2) including an external camera-based tracking sensor; a hand-tracking motion sensor (Leap Motion Controller) affixed to the front faceplate of the HMD; and a computer (we used a quad-core 2.6 GHz Intel Core i7 Mac Mini). The working environment is shown in Figure 2. The user wearing the HMD is seated in front of a desk, facing the HMD's tracking sensor at about one meter's distance ahead. The user typically keeps one hand on the keyboard for switching modes and triggering actions, and the other hand in the air for gestural motion tracking.

The HMD provides 1080p resolution per eye, 100° field-of-view (FOV), 75Hz refresh rate, and minimal motion blurring [21]. The external tracking system provides accurate and low-latency orientation and positional coordination over the entire working environment. The Leap Motion Controller provides sub-millimeter tracking of hands and fingertips, including gesture recognition, over a wide 150° field of view with an effective range of roughly 25 to 600 millimeters (however hand detection and tracking works best when the user's hands are well within this range and closer the center of the user's view). It also provides an infrared video feed capable of supporting see-through AR (see Figure 3).

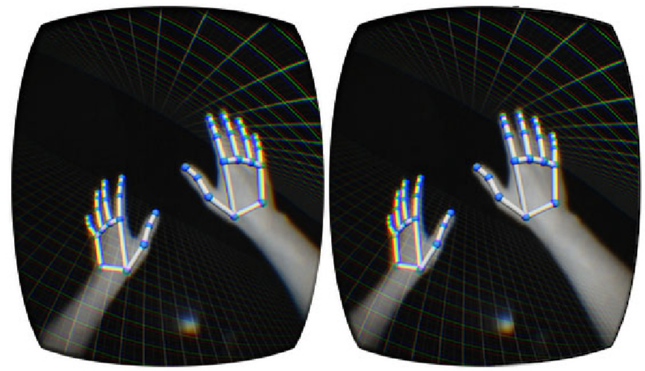

Figure 3: In-HMD view of virtual hand models overlapping infrared imagery of the real hands [15].

3.2 Software Architecture

The system's software was developed with Unity® 3D v.5. The software continuously extracts tracking information and raw infrared imagery through the Leap Motion API. The extracted information is used to drive the gestural augmentations that generate virtual forms within the context of real-world imagery captured by the sensor's two infrared cameras. The output is rendered onto the Oculus Rift display at 75Hz via Unity's Oculus Rift API.

The hand tracking data is used to construct virtual hand models in estimated posture, position, orientation, and velocity of every bone, finger, and fingertip, relative to the virtual position of the Leap device. Hand models are visualized as virtual skeletons and overlaid onto Leap Motion's video pass-through imagery, with tracking confidence represented via the opacity of the virtual hand models. These virtual hands are rendered to the HMD in the same stereoscopic 3D space as user-generated sculptural forms.

3.2.1 3D Interface Design. The principal focus of interaction is freeform, continuous mark making in space, with one of three physical augmentation brushes as described in the next section. However the dynamics, shape, and appearance of these brushes are partly determined a number of settings that are configured through a set of interface palettes, which we describe first.

3.2.2 Palette Mode. All configurable system settings are accessed through the system's three palettes (Figure 4). When requested (by pressing the spacebar key), three large palettes are situated in space at an approachable distance from the user, at an accessible scale, and in a spatial cockpit arrangement to take advantage of the HMD's wide field of view. The palettes situate instantly familiar 2D desktop metaphors of clickable buttons and draggable sliders in the 3D space.

The palettes offer a breadth of options to maximize the user's creative control over the brush's properties. The leftmost palette modifies a brush's shape, orientation, scale, extrusion and thickness variation. The right palette selects color and material. The central palette fine-tunes critical parameters of the dynamic behavior of the current brush. Changes made with the palettes are promptly visualized in the form and movement of all active brushes.

Pressing the spacebar once more hides the palettes and returns to the unobstructed drawing mode. The two modes keep the virtual creations and palettes separate and prevent any overlap or occlusion. An additional overlay can be used to save, load, or reset the current scene.

Users can also swipe the hand vertically just in front of the HMD to toggle between VR and AR modes. The swipe gesture semantically corresponds to its function and makes it easy to transition between modes while drawing or editing.

Figure 4: In-HMD view of the configuration palettes.

3.2.3 Dynamics-Based Interaction Design. Three types of brush prototypes inspired by dynamic models are presented in this system: spring-mass brush, ribbon brush, and rope brush. The spring-mass brush builds upon Snibbe's *Dynasculpt* model [25] and adapts its concept to an immersive platform with freehand 3D interaction. The ribbon and rope brushes also utilize dynamic simulation-driven models inspired by real-world physical phenomena. The three brush prototypes were chosen to evaluate the creative potential of connecting physically inspired dynamics with the creation of form in ways that are only possible in virtual space. Although focus is primarily on airborne gestural strokes of the tracked fingertips, specific keys on the physical keyboard are also used as a convenient mode of invoking subsidiary functions.

Spring-Mass Brush. Snibbe's *Dynasculpt* was a 3D adaptation of Haeberli's *Dynadraw* application, which focused on exploring how dynamic models transform the creative process. Our system's spring-mass brush prototype is based on the same spring-mass-damper model, but differs from prior work in that users' hand movements provide direct 3D input and its immersive display allows virtual forms to directly materialize at the user's fingertips, including multiple fingertips simultaneously. Fingertips of all extended fingers in view are respectively augmented by a virtual spring with a mass attached to its other end (Figure 5). The line that extends from the fingertip to the mass represents a spring that can stretch and contract as it tows the mass along. The attached spring and mass follow the fingertip in accordance with its dynamic settings as long as the finger remains extended. The masses attached to each finger can collide with those of other extended fingers, and rebound.

To begin drawing with the brush, users must press their designated "draw" key (the left Control key by default). The 3D stroke begins from the virtual mass and continues along its 3D path while the draw key is held down (Figure 6), and ends when the key is lifted. The virtual brush "springs" into action once the distance between the fingertip and the mass grows past its state of equilibrium. The virtual matter that appears in its trail is promptly erased if the brushstroke is cut prematurely and fails to travel a pre-defined minimal distance.

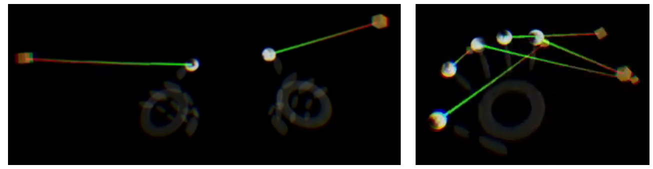

Figure 5: (Left) Virtual masses attached to fingertips by virtual springs. (Right) All extended fingers receive masses.

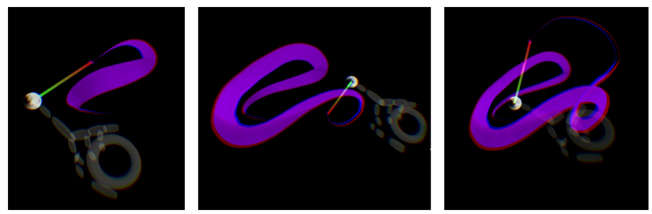

Figure 6: A drawing progressing with the spring-mass brush.

Figure 7: Examples of sketches showing greater degree of control. Both were created by an artist on the first trial of the system, after less than one hour of experimentation.

Users are given direct control over three specific parameters that define the brush's character and quality of movement: 1. Weight of the mass, 2. Spring constant, 3. Damper value. Other subsidiary factors such as air drag are kept at an optimal constant. Adjustments in parameter values are made through the dynamics palette, and any changes are instantly applied and observable in the brush's behavior. The default base shape is a flat rectangle, chosen for the ribbon-like forms that reveal dynamic changes in orientation it creates. The default extrusion type is a flare, which shows variations in thickness with less computational power than the velocity type (which adjusts the stroke's thickness according to speed of the stroke). The shape and extrusion type of the brush, as well as its stroke weight and thickness contrast level are changeable via the palette.

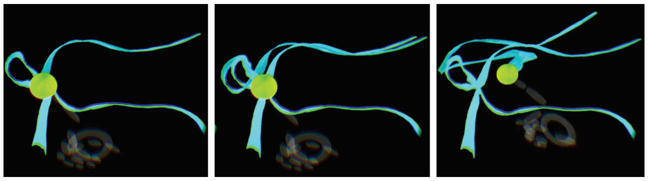

Figure 8: A ribbon is captured in its current position and another one immediately appears in its place.

Ribbon Brush. The ribbon prototype was inspired by rhythmic gymnasts' manipulations of the ribbon, with which they create dynamically changing shapes in mid-air to augment their performance. While the ribbon is in constant motion, it routinely holds its form long enough to appear magically suspended in air. Photographs sometimes manage to capture these exquisite moments in a ribbon's ephemeral dance. The ribbon brush prototype attempts to capture this fleeting beauty of a ribbon at a select moment in time in its full-dimensional form.

In the prototype, the user's extended fingers are virtually augmented with a long strip of cloth in the form of a ribbon (Figure 8). One end of the ribbon is fixed onto the fingertip like a gymnast's ribbon on the end of a stick. The ribbon exists in a zero gravity zone and stays still in the air in the absence of movement. When the finger or hand moves, the ribbon naturally tugs along with it. Users have the power to freeze the dancing ribbon in time and space by pressing the designated "capture" key. Multiple active ribbons are captured simultaneously and promptly replaced by newly generated ones.

Rope Brush. The rope model was inspired by how rope as a material is skillfully manipulated and appropriated for a great variety of purposes. Rope-based physics is prominently used in game development to simulate the real-world behavior of malleable linear objects in dynamic contexts. A piece of rope invites tactile engagement and manipulation, and our hands have a highly developed understanding of how it behaves and what we can do with it. When both hands are closed to form two fists, a virtual rope appears that loosely spans from one hand to the other, with its ends fixed to the palm of each hand (Figure 9). While both hands remain closed, the rope dangles in between the two hands. The rope may be stretched, twisted, and swung up and down by naturally moving one's hands (Figure 9).

The rope turns into a static mesh the moment both hands rope is let loose, users must close both hands again to generate another rope. The rope's length is determined by the distance between two hands the instant it is being made.

4 INITIAL EXPLORATIONS

The spring-mass prototype was informally tested by students, artists, and designers during various stages of its development. Most had never used a VR or AR system for virtual content creation before and found the hand-based 3D interface and interaction techniques highly intuitive and enjoyable; many voluntarily came back to test upgrades or new features.

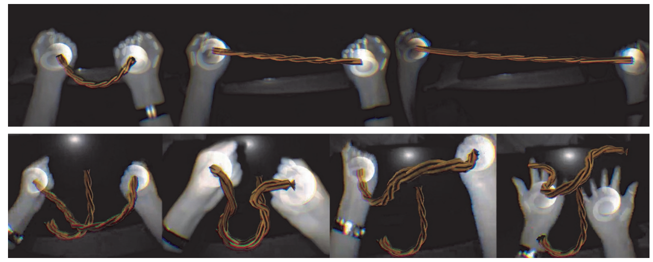

Figure 9: (Top): The rope is being held by its two ends and stretched. (Bottom) The rope, once swung up then released, stays frozen in its spot.

Users were quick to begin using and experimenting with the brush, though some found it challenging to exercise fine-grained control. Based on user feedback, the 3D positions of active fingertips were made more prominent by adding distinct white spheres as visual indicators, and the virtual representation of the spring was made more readily distinguishable through brighter and more vivid colors. The default dynamic parameters of the spring and mass were also adjusted to better match general user expectations and preferences.

While some users were immediately adept at handling the 3D palette interface, others had trouble determining how far they needed to reach to click buttons (an apparent misjudgment of depth). In the absence of physical feedback, some users needed more practice in manipulating slider handles to adjust their values with precision. Visual cues and feedback such as motion effects that mimic a button being clicked, or changes in color brightness of slider handles when pressed upon, are amplified to facilitate these interactions.

The layout of the palettes including the placement, scale, and trigger distance of its buttons and sliders were also reconfigured and adjusted to make it more accessible for all users. Toggle buttons for each palette were added for users who did not want to always keep all palettes open at once.

Originally the palettes had been conceived as co-existing with the space of the 3D sculptural forms being made, however it was immediately apparent in user trials that this negatively constrained the spaces in which users worked and caused distracting occlusions. Giving users the ability to freely move the palettes wherever they want appeared to be a probable solution, but we eventually settled for the simpler solution of dividing the two modes.

5 EVALUATION

Following these initial studies, expert interviews were conducted for a more informed analysis of the system's design and approach. This was followed by a broader user study to obtain an objective assessment of the system's usability and user experience from the perspective of prospective users.

5.1 Expert Interviews

We sought expert opinions as an efficient and effective means of assessing the following: (1) The conceptual originality of the system's approach; (2) The effectiveness of its interaction design and technical realization; (3) The effectiveness of the VR versus AR modes; (4) Its viability as an artistic tool, or other potential applications; (5) The identification of specific areas for continued development, or critical factors that may have been overlooked in the design.

5.1.1 Selected Experts. Two experienced professionals–an artist who works with immersive systems and a research scientist specializing in AR and VR interactions–were consulted independently for proper assessment and feedback on the above issues. Dr. Ji is a 3D sculptor, media artist, and educator with over 10 years of research experience in immersive art and technologies and over 20 years of experience in sculpture. Dr. Ha is a researcher and entrepreneur in immersive technologies with over 10 years of research experience in Mixed Reality (MR), AR, and 3D user interaction.

5.1.2 Procedure. The expert evaluation was conducted in four stages: (1) a brief overview of related works (5 min), (2) a video overview of the spring-mass prototype and its features (5 min), (3) a trial run of the working prototype (20 min), and (4) an in-depth interview (30~40 min). System trials were video-captured and interviews were audio-recorded with prior consent. The interviews were open-ended and loosely structured around a list of questions to facilitate discussion.

5.1.3 Results and Analysis. Dr. Ha found the spring-mass prototype highly engaging and fun to draw with, and felt more motivated and proficient in drawing with the 3D brush than with a pencil and paper. He was particularly struck by its intuitive and playful interactivity and thought it would be a promising creative tool for children. He found the 3D interface design effective in how it organized and presented complex information, and opportune for an immersive environment. Dr. Ha considered the use of fingertips somewhat arbitrary and suggested potentially using virtual or physical props that users could easily grasp and maneuver. Moreover, in the prototype's current state, he thought the real-world backdrop in AR mode was more distracting than helpful; and the greater advantages of an AR modeling environment were in his view not fully explored. Dr. Ji also identified playfulness–a quality she described as "the joy of creating"–as one of the system's greatest assets. She noted how the augmented dynamic behavior of the brush expanded the expressive capacity of hand movement and made it easy to create highly complex, sweeping curve, whereas creating such curves with such immediacy and spontaneity was very difficult even for advanced users of traditional NURBS-based modeling tools. She thus saw strong potential applications of this modeling approach in rapid 3D sketching and prototyping for sculptors and architects. She posited that it would be advantageous for creating rough sketches to be later edited refined in high-end modeling software, and even 3D-printed as physical mock-ups. However to strengthen it as an artistic tool Dr. Ji stressed the importance of offering a diverse range of dynamic brushes and enabling more sophisticated control over their dynamic behavior. She highly recommended a two-handed interface that allowed one hand to control the model's orientation while the other sculpts or draws.

In contrast to Dr. Ha she found it preferable to work in AR than VR mode. Although she recognized that the VR mode could permit users to fully customize their virtual workspace, she suggested the AR mode offered four significant advantages: (1) an intuitive sense of shape, scale, and position relative to one's body and hands, (2) real-world dimensions for models being designed for a specific space, (3) the ability to visually identify supplementary means of input such as the keyboard, and (4) awareness of the presence of others, which opens up the potential for collaboration.

5.2 User Study

The main purpose of the general user study was to assess the system's ease of use, the effectiveness of its interaction design, and user satisfaction.

5.2.1 Participants. A total of ten graduate students–six male, four female–participated in the study. Half of the participants had used 3D modeling software before, mostly in a beginner capacity. Three had experience with VR or AR systems, and none had any experience in digital sculpting. Only one student had substantial experience working with physical media for creative output.

5.2.2 Procedure. The user study was conducted in the following six steps: (1) video-based introduction to the spring-mass prototype and its main features (5 min), (2) training and practice in using the spring-mass brush (10 min), (3) free doodling session (10~15 min), (4) video overview of the ribbon and rope prototype, (5) System Usability Scale (SUS) questionnaire, and (6) short answer questionnaire.

SUS is widely used across fields as simple and robust tool for a general assessment of a system's usability and learnability [3]. The questionnaire consists of ten statements and uses a 5-point rating scale ranging from "strongly disagree" to "strongly agree". Instructions were added to the top of the SUS form to have people record their most immediate and instinctive responses, as was recommended by [2]. The short answer questionnaire consisted of open-ended questions including what users liked and disliked most about the system.

5.2.3 Results and Discussion. The average SUS score was 67.5, which lies in between the threshold of an "OK" and "Good" result [2]. For detailed analysis, mean scores and standard deviations were calculated for each item. The item that received the highest score (mean: 4.1, SD: 0.7) indicated that users did not find the system unnecessarily complex. High scores were also given to the system's consistency (mean: 4, SD: 0.63) and the user's confidence in using it (mean: 4, SD: 0.45). Items that received the poorest ratings suggested that many found the system difficult to use (mean: 3.3, SD: 1.19) and that it required a lot of learning (mean: 3.3, SD: 1.0). This particular response was unexpected since preliminary informal testing had suggested the very opposite. We believe that the perceived usability of the system dropped because of the increased set of features in the palettesâĂŞmore time is spent configuring advanced options in these interfaces, drawing attention away from the simplicity of the core sculpting gesturesâĂŞand thus it may be preferable to initially present a curated palette of popular brush modes rather than a fully-featured configuration panel. Participants were clearly very quick to understand how the brush works and began drawing at once when given the opportunity. They became rapidly adept at maneuvering the brush, and enjoyed playing with it and discovering forms it was capable of creating. Many appreciated having direct control over the dynamic behavior of the brush and the freedom to tweak it to their liking. Some noted that the brush prototype is not ideal for detailed operations, and that it would take time to gain sufficient mastery for more sophisticated control. What users identified as liking most about the system was the fully 3D nature of drawing and the ability to take any position-tracked perspective desired. What was most often criticized was the 2D palette interface: some had difficulty reaching certain buttons or sliders, or would accidentally trigger others, and some found it tiresome to learn all its options. Most agreed that having both VR and AR modes was advantageous: the VR model helped focus concentration on the drawing, while the AR model granted a better sense of scale. Some noted that the AR mode would be beneficial for modeling works intended for an actual physical space.

6 DISCUSSION

During the evaluation we observed how, with nuanced maneuvering, users were able to steer the virtual mass-spring system to fluidly create curvaceous strokes, even when stretching much further than the finger's scope of movement. Users generally showed instant familiarity and intuitive understanding of its mechanics, and gained greater command of the brush for more nuanced expressions with a short amount of practice. Results showed immediate expressivity that would require extensive training to achieve with traditional 3D software.

The intuitive modeling process, however, was intermittently interrupted due to the system's susceptibility to errors in hand detection and tracking. In particular, users' gestural strokes could be cut off prematurely due to self-occlusion problems in the hand tracking. When users were informed about why this was happening, however, many found ways of working around these limitations and through conscious effort grew more proficient in keeping fingertips visible while wielding the interactive brush. We anticipate future improvements to tracking hardware/software to overcome this issue. In the interim an undo key was also added as an edit function to allow users to delete any 3D strokes that were abruptly cut short.

The interaction design for the palettes also made their functioning vulnerable to tracking errors. More stable and robust palette designs that enable swift changes in brush properties and fluid transitions between modes would be vital for robust use of the dynamics-driven brush. Substituting the 'draw' key with a foot pedal or voice-activated input would also free users to draw with both hands and also control the stroke weight.

The ribbon and rope prototypes show the exciting new creative opportunities that emerge from expanding our dynamic-driven approach to virtual form creation. Their interaction designs take advantage of our bodily intuitions in manipulating various objects and material and the freedom to suspend the laws of physics in virtual contexts. The spontaneous, expressive forms users are capable of creating with these systems are immensely difficult to approximate with conventional modeling tools. In their current state, however, the prototypes fall short of showing the full creative potential of this approach. Enhanced realism of virtual simulations, a diverse range of changeable form factors and interaction methods, and sophisticated controls over dynamic behavior would greatly expand their utility and expressive capacity for artistic output.

It would be beneficial to conduct a more comprehensive and meticulously designed user evaluation with an updated spring-mass prototype to specify and validate the advantages of using a brush that uses dynamic models to augment gestural input as opposed to one without any gestural augmentation. It would also be insightful to compare differences in user performance in learning and creating with the prototype when a monoscopic desktop monitor is used as opposed to a fully immersive display.

7 CONCLUSION

An immense effort was put into making the physical interaction as fluid and seamless as possible in the above systems. Augmenting gestural strokes with dynamic simulations for immersive modeling has proven to encourage creative exploration and experimentation. Gestural interaction and dynamic models drawn from real-world behavior engage our natural spatial instincts and intelligence toward the shaping of form. The brush prototypes successfully combined physically inspired interaction techniques and the unique plasticity the virtual world to extend our expressive capacity and create new forms of expression. Users generally found the experience creatively satisfying and liberating. Dynamic interactive brushes may find application in virtual sculpting, design ideation, rapid prototyping, and authoring animated virtual environments.

Each prototype in its current state still imposes a strong visual style specific to its dynamic model. Much more experimentation with dynamic parameters and applicable forces would be necessary to find robust ways of diversifying its creative output.

As identified by expert interviewee Ji, supporting the export of models will be essential both for refinement and for re-use in other environments or for 3D printing. Moreover, supporting collaborative creation in a shared augmented space could add significant value to the experience. As identified by expert interviewee Ha, the prototypes would also benefit from taking more advantage of the unique affordances of an AR environment to enable richer forms of interaction that further integrate the physical and virtual, such as detecting recognizable surfaces and objects in the physical context and granting them functional roles in the simulated dynamics.

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