Bimanual Interactions for Surfacing Curve Networks in VR

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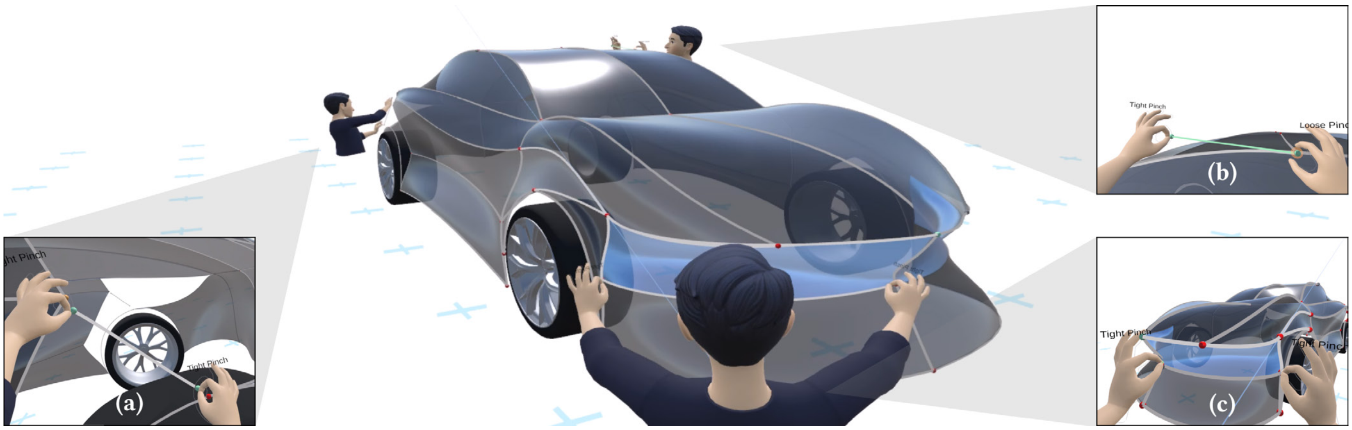

Figure 1: We propose a novel interactive system for authoring 3D shapes quickly and easily with bare hands in virtual reality (VR). With bimanual hand gestures based on the metaphors of physical wire bending and film wrapping, the user can (a) create and (b) modify curve and (c) surface networks.

Abstract

We propose an interactive system for authoring 3D curve and surface networks using bimanual interactions in virtual reality (VR) inspired by physical wire bending and film wrapping. In our system, the user can intuitively author 3D shapes by performing a rich vocabulary of interactions arising from a minimal gesture grammar based on hand poses and firmness of hand poses for constraint definition and object manipulation. Through a pilot test, we found that the user can quickly and easily learn and use our system and become immersed in 3D shape authoring.

CCS Concepts

• **Human-centered computing → Interaction techniques**.

Keywords

VR; bimanual gesture; Bézier curve network; surface modeling

ACM Reference Format:

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1 Introduction

In product design, seeing the actual sizes and proportions of 3D shapes is crucial. Traditionally, this has necessitated physical prototyping, which demands significant time and effort. However, virtual reality (VR) is emerging as a new medium for 3D design, enabling the immediate visualization of 3D products at their true scale without the need for additional work.

One method for creating 3D shapes in VR is based on the trajectories traced by hands or controllers [1, 7, 8, 14, 15, 22–24, 27, 32, 34, 35]. While being fast and direct, it requires the coordinated movement of the wrist, arm, and shoulder joints [3], which can be challenging to perform precisely in midair. An alternative method is based on control points [4, 6, 13, 19, 25, 28, 30, 33]. While providing an easier and more precise means of creating and modifying 3D shapes, it can be indirect and time-consuming, as it involves individually adjusting control points with high degrees of freedom.

We propose a novel interactive system that enables intuitive creation and modification of curve and surface networks using bimanual interactions (Figure 1). In our system, the user can quickly learn hand gestures inspired by actual craft activities such as wire bending and film wrapping, and become immersed in shape authoring, utilizing the high expressiveness of bare hands. Furthermore, the user can make precise modifications to their shapes through a combination of constraint definition and object manipulation, which are differentiated by the firmness of hand poses.

2 RELATED WORK

In this section, we explain previous works on midair free drawing, control point manipulation, and physics-based interactions for authoring 3D shapes in immersive environments, and how they relate to this study.

The most common interaction methods for creating 3D shapes in VR are midair free drawing using hands [27] or VR controllers [1, 8, 16]. However, midair drawing can be challenging due to the lack of depth cues and physical surfaces [3]. Therefore, visual guides such as lines, cylinders, or grids can be displayed to enhance depth perception [23]. Also, drawn trajectories can be fitted to predefined lines [35] or planes [22], or connected into 3D curve networks [34], but there are concerns that such corrections may distort the user's intent. Moreover, to improve the accuracy of input trajectories a tablet device [2, 7, 18, 31] or the palm of the hand [14] can be used as physical drawing surfaces within VR. However, if the outcome does not match the desired shape, parts of, or the entire curve must be redrawn repeatedly.

The other interaction methods are control point manipulations [28] that allow for the iterative modification of 3D shapes without redrawing them entirely, thus enabling gradual convergence towards the desired shape. However, manually creating and adjusting every control point still consumes a significant amount of time. To alleviate this problem, some systems support the expansion of 2D shapes into 3D space [13], possibly through interactions utilizing midair hand gestures in conjunction with multi-touch gestures on a 2D input surface [6]. Nevertheless, these methods still involve the indirect manipulation of shapes through control points and significantly differ from natural crafting activities. In this study, we aim to design a system that facilitates an intuitive manipulation of 3D shapes using real-life hand gestures.

People naturally use both hands for precise manipulation [11]. These actions can be emulated in immersive environments through the use of physical metaphors. For instance, by applying the tape drawing technique, widely used in the automotive industry to draw large curves on flat walls, to a digital environment [5], some systems enabled creation of 3D curves on walls [9, 10]. Moreover, by extending such interactions into 3D space, other systems enabled creation of 3D curves directly in midair [16]. In such systems, the user can invoke operations for creating and manipulating 3D objects [17, 29] and defining geometric constraints for precise manipulation of 3D objects [12] with natural hand poses.

In this study, by extending the curve-based *WireSketch* system [21], we propose an interactive system for authoring 3D shapes that include surfaces. We utilize hand poses resembling grasping objects of various shapes in real-life for intuitive selection of the object to interact with. Moreover, we leverage the firmness of hand poses for seamlessly going back and forth between defining a constraint that fixes the position and/or direction of the object, and manipulating the object under such a constraint.

3 SYSTEM

In this section, we introduce a novel interactive system for authoring 3D shapes quickly and easily with bare hands in VR with bimanual hand gestures designed based on the metaphors of physical wire bending and film wrapping. In the following subsections, we describe the components the user can interact with, a grammar of hand gestures for defining constraints and manipulating objects, and a vocabulary of interactions for authoring curve and surface networks that arises from this grammar.

3.1 Interface & Hand Gesture

In our system, the interactive components that the user can manipulate include control points, wires, and surfaces (Figure 2). Each wire is composed of four control points, and each surface is composed of four boundary wires and four floating control points. the user initially creates and manipulates wires to form curve networks, and subsequently uses these curve networks to create surfaces.

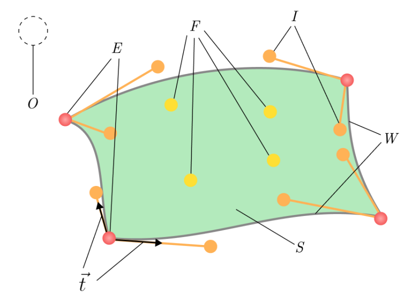

Figure 2: System Interface. O: midair, W: wire, S: surface, E: end control point, $\vec{t}$: tangent of wire on the end control point, I: inner control point, and F: floating control point.

The hand gestures in our system are categorized into *pinch*, *grip*, and *clamp*. The pinch gesture specifies the position of a control point (Figure 3a, d). The grip gesture specifies the position and tangent of a wire (Figure 3b, e). Lastly, the clamp gesture specifies the position and surface normal at the boundary wire (Figure 3c, f).

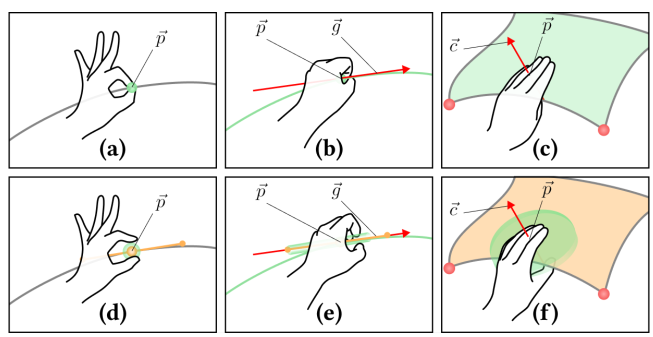

Figure 3: Hand gestures. (a) Tight-pinch gesture specifying position ($\vec{p}$), (b) tight-grip gesture specifying position ($\vec{p}$) and grip direction ($\vec{g}$), (c) tight-clamp gesture specifying position ($\vec{p}$) and clamp direction ($\vec{c}$), (d) loose-pinch gesture specifying position ($\vec{p}$), (e) loose-grip gesture specifying position ($\vec{p}$) and grip direction ($\vec{g}$), and (f) loose-clamp gesture specifying position ($\vec{p}$) and clamp direction ($\vec{c}$). Objects that are manipulated by tight gestures are colored green. Objects that are constrained by loose gestures are colored orange.

A tight gesture manipulates a component directly. A tight-pinch gesture (Figure 3a) can only move the control point being pinched, without affecting its direction. A tight-grip gesture (Figure 3b) can both move the wire being gripped and rotate its tangent direction. Lastly, a tight-clamp gesture (Figure 3c) can both move the surface being clamped and rotate its orientation.

A loose gesture only defines a geometric constraint on a component. A loose-pinch gesture (Figure 3d) can fix only the position of the control point being pinched, leaving its direction free to change. A loose-grip gesture (Figure 3e) can fix both the position and tangent direction of the wire being gripped. Lastly, a loose-clamp gesture (Figure 3f) can fix both the position and orientation of the surface being clamped.

In our system, most bimanual interactions engage the two hands asymmetrically following the kinematic chain model [11], where a component is constrained with a loose gesture with one hand first and manipulated with a tight gesture with the other hand shortly after. In cases where a component does not need to be constrained, bimanual interactions engage the two hands symmetrically [20].

3.2 Create & Delete Curve

The user can create a linear wire with a two-handed tight-pinch gesture in midair akin to pulling (Figure 4). In addition, the user can create a circular wire with loose-grip and tight-pinch gestures in midair akin to winding (Figure 5). Finally, the user can delete a wire with a two-handed tight-grip gesture akin to crumpling (Figure 6).

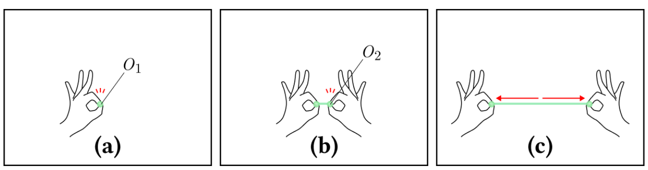

Figure 4: Create a linear wire. The user (a-b) tight-pinches with both hands close together in midair (O_1, O_2) to create a straight wire, and then (c) stretches it into a desired line.

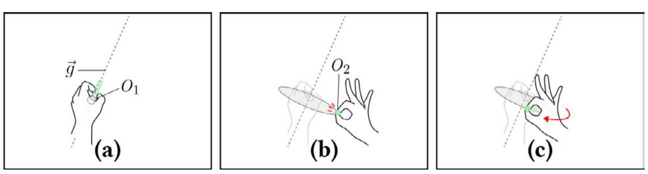

Figure 5: Create a circular wire. The user (a) loose-grips in midair (O_1) to set an axis direction ($\vec{g}$), and then (b) tight-pinches at the starting position (O_2) of the circular wire and (c) rotates the point around the axis.

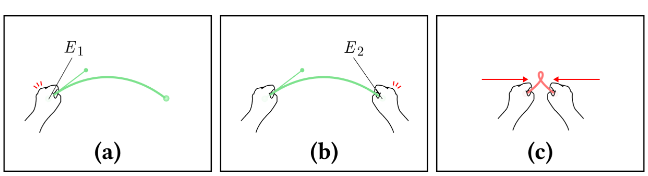

Figure 6: Delete a wire. The user (a-b) tight-grips both end control points of a wire (E_1, $E2$), and then (c) brings them sufficiently close to each other.

3.3 Manipulate Curve

The user can freely manipulate a wire or its end control point using a tight gesture with one hand (Figure 7). For precise manipulation, the user can first define a constraint with a loose gesture, then directly manipulate a control point under the constraint with the other hand (Figure 8). During this operation, if the tangents of wires become sufficiently close to parallel, the tangent of the wire being manipulated is automatically aligned with the other tangent.

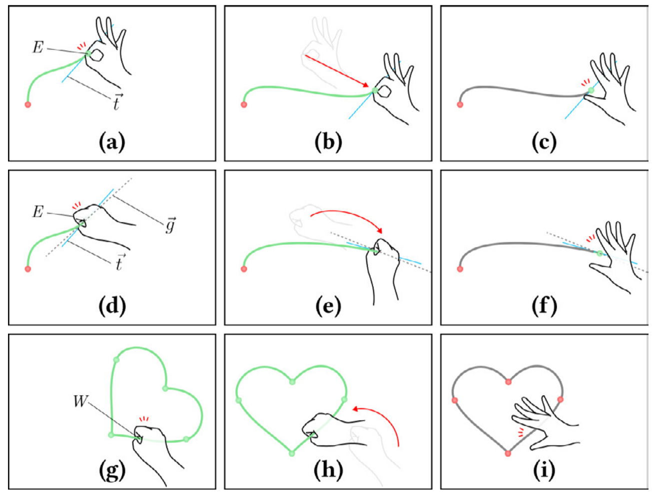

Figure 7: Move an end control point. The user (a) tight-pinches an end control point (E) and (b-c) moves it to change its position without changing its tangent ($\vec{t}$). The user (d) tight-grips an end control point (E) and (e-f) moves it to change both its position and tangent ($\vec{t}$). The user (g) tight-grips a wire (W) somewhere in the middle to (h-i) move and rotate the entire curve network without deforming.

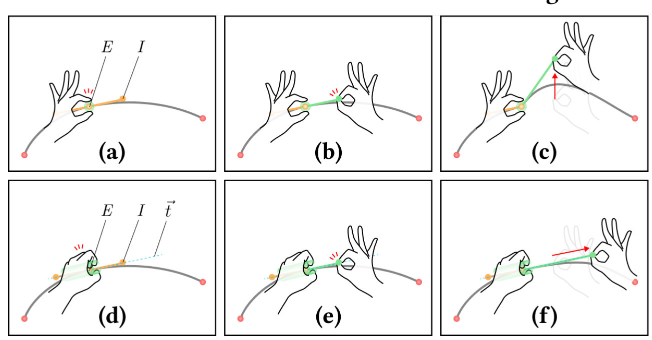

Figure 8: Move an inner control point. The user (a) loose-pinches an end control point (E) with one hand and (b) tight-pinches an adjacent inner control point (I) with the other hand to (c) move it freely. The user (d) loose-gripes an end control point (E) with one hand and (e) tight-pinches an adjacent inner control point (I) with the other hand to (f) move it along the constrained tangent ($\vec{t}$).

The user can connect wires (Figure 9a-c) or subdivide a wire (Figure 9d-f) to compose a curve network. Also, the user can separate a connected wire with loose-pinch and tight-grip gestures (Figure 10a-c) or loose-grip and tight-pinch gestures (Figure 10d-f), depending on whether to separate a wire from a fixed end control point or an end control point from a fixed wire, respectively.

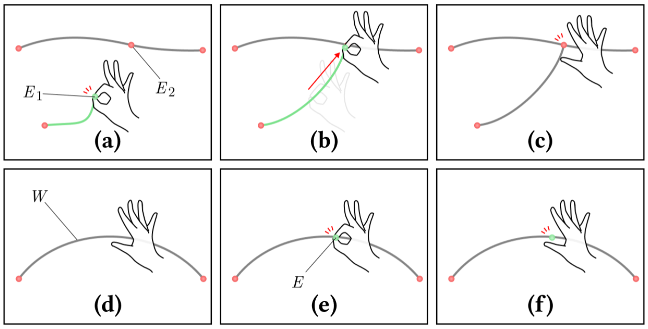

Figure 9: Compose a curve network. The user (a) tight-pinches an end control point (E_1) and (b) releases it sufficiently close to another end control point (E_2) to (c) merge the end control points. The user (d-e) tight-pinches anywhere on a wire (W) to (f) create a new end control point dividing the wire into two.

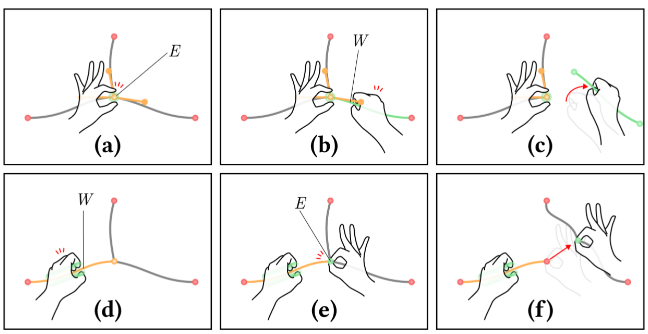

Figure 10: Separate a wire from a curve network. For multiple wires connected to a single end control point, the user (a) loose-pinches the end control point (E) and (b) tight-grips one of the wires (W) with the other hand to (c) separate the wire from the end control point. In the same situation, the user (d) loose-grips a wire (W) and (e) tight-pinches the end control point (E) with the other hand to (f) separate the other wires from the end control point.

3.4 Create Surface

The user can create a surface using wires in a curve network. The user can select a profile wire with a loose-grip gesture (Figure 11), and then create a surface by connecting the profile wire to another wire as if wrapping (Figure 12), by sweeping the profile wire (Figure 13), or by revolving the profile wire (Figure 14).

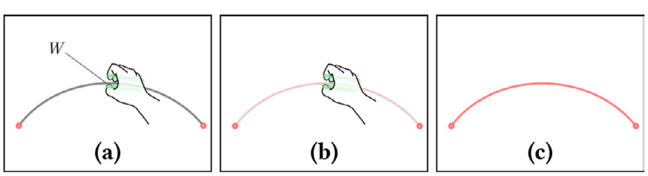

Figure 11: Select a profile wire. The user (a) loose-grips the wire (W) and (b) waits for a short time (c) until it turns red, indicating the state in which a surface can be created from it.

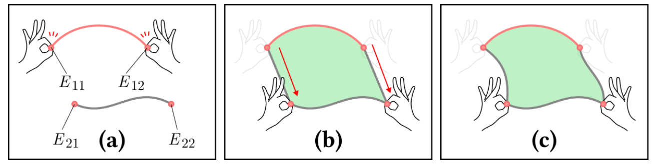

Figure 12: Create a loft surface. The user (a) tight-pinches the two end points of a selected wire ($E_1 1$, $E_1 2$), and (b) bring them close to the end points of another curve ($E21$, $E22$) to create a loft surface connecting the two curves. (c) If there are other curves bridging between the two curves, they are used as guide curves.

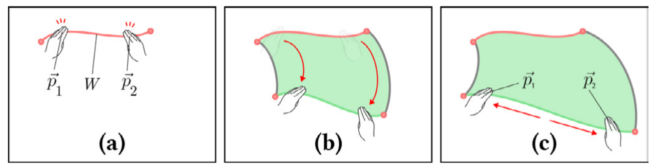

Figure 13: Create a swept surface. The user (a) tight-clamps a selected wire (W) with two hands ($\vec{p}_1$, $\vec{p}_2$), and then (b) moves it along a desired trajectory. (c) The user can also adjust the scale of the profile wire by increasing and decreasing the distance between the two hands.

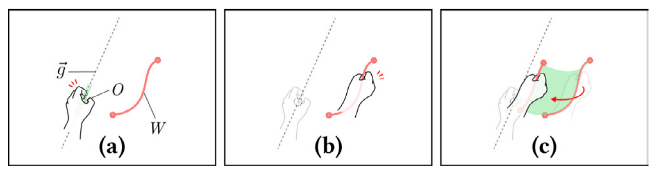

Figure 14: Create a revolved surface. The user (a) loose-grips in midair (O) to set an axis direction ($\vec{g}$), and then (b) tight-grips a selected wire (W) and (c) rotates it around the axis.

3.5 Manipulate Surface

Similar to curve manipulation, the user can freely manipulate a surface by one of its boundary wires with a tight-clamp gesture (Figure 15). For precise manipulation, the user can first define a constraint with a loose gesture, then directly manipulate a floating control point under the constraint with the other hand (Figure 16). The user can bend an adjacent surface with loose-clamp and tight clamp gestures (Figure 17). During this operation, if the cross-boundary slopes of the two surfaces become sufficiently close to parallel, the cross-boundary slope of the surface being manipulated is automatically aligned with the other slope.

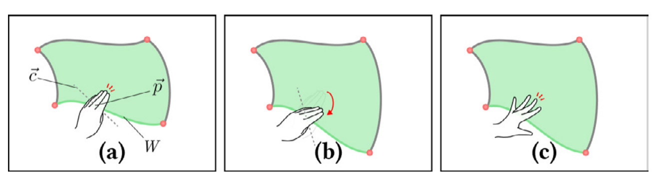

Figure 15: Move a boundary wire. The user (a) tight-clamps a boundary wire (W) of a surface and (b-c) moves it freely. The two wires connected to the clamped wire are deformed following the end control points of the clamped wire.

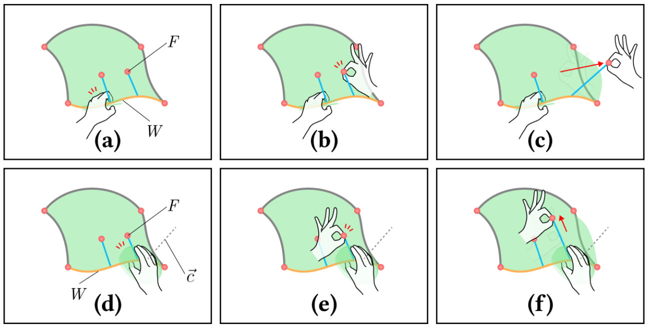

Figure 16: Move a floating control point. The user (a) loose-grips a boundary wire (W) of a surface with one hand and (b) tight-pinches an adjacent floating point (F) with the other hand to (c) move it freely. The user (d) loose-clamps a boundary wire (W) of a surface with one hand and (e) tight-pinches an adjacent floating point (F) with the other hand to (f) move it along the constrained direction at the boundary wire.

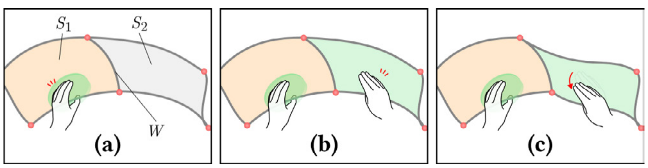

Figure 17: Bend a surface. The user (a) loose-clamps a surface (S_1) with one hand to fix the surface and (b) tight-clamps the adjacent surface (S_2) across the boundary wire (W) and (c) bend the adjacent surface.

4 IMPLEMENTATION

We implemented our wires as cubic Bézier curves and surfaces as bicubic Bézier patches, and referred to the mathematical formulation and optimization techniques of *The NURBS Book* [26]. Our system was developed in the Unity game engine and operated on the Meta Quest 2 VR headset with hand tracking support.

5 PILOT TEST

We conducted a pilot test to check the learnability and usability of our system as a 3D shape authoring tool, compared to an existing VR system based on controllers. We collected product design concepts from participants along with their initial qualitative feedback on the system.

5.1 Participant

Five industrial design students (2 males, 3 females, aged 19-22) who were interested in product design participated in the pilot test. All participants had previous experience with VR.

5.2 Procedure

We compared our system with *Gravity Sketch* [28], a commercial controller-based system for 3D modeling in VR. For each system, participants spent 30 minutes learning about its features through a tutorial provided by the authors. Subsequently, participants spent 1 hour authoring freeform shapes in each system while using every feature at least once. At this point, we conducted interviews to gather their initial feedback on each system. Afterward, they spent the next 3 days designing products using our system (Figure 18).

5.3 Findings

We discuss three key findings from the interviews and observations from the pilot test regarding the learnability and usability of our system relative to the existing controller-based system.

Learnability and memorability. In the controller-based system, participants experienced difficulty learning and memorizing many functions that were mapped to a hierarchy of menus and buttons (P1, P2, P5). However, In our system, the bare hand gestures were similar to real-life operations, so they were easier to learn and memorize (P1, P2, P4, P5).

Immersion and ergonomics. In the controller-based systems, participants were often distracted by navigating through menus and buttons for accessing different functions (P1, P2, P3). However, in our system, participants could stay focused on designing shapes as they could create, constrain, manipulate, and delete objects solely through hand poses and firmness of hand poses (P2, P5). Additionally, compared to using bare hands, using the VR controllers could be more physically demanding due to their weight (P5).

Speed and fidelity. In the controller-based system, midair sketching was quick (P3, P5), but fine-tuning the rough sketches toward the desired shapes required significant time and effort (P1, P3). However, in our system, while creating a single wire required slightly more time and effort than sketching a single rough stroke, it was overall substantially easier and faster to complete a 3D shape that is a well-connected network of curves and surface. (P2, P3, P4).

6 CONCLUSION

VR is emerging as a new design space, allowing designers to directly visualize and interact with the real sizes and the real proportions of 3D shapes. However, despite the expansion into 3D space, the menu- and button-based interfaces operated with handheld controllers are unable to take advantage of the full potential of the medium.

In this study, we proposed a novel interactive system for designing 3D shapes in VR featuring intuitive bare-handed bimanual interactions that closely resemble the way people grasp and handle objects in real life. From only three simple hand poses (pinch, grip, and clamp), and two levels of firmness of hand poses (loose and tight), we successfully designed a rich vocabulary of interactions for creating, constraining, manipulating, and deleting networks of 3D curves and surfaces.

We conducted a pilot study and interviewed the participants for a qualitative evaluation of our system in comparison with an existing controller-based system. Our initial findings indicate that using bimanual interactions for authoring 3D shapes can be easier to learn and provide more freedom and immersion in the design process compared to menu- and button-based interfaces.

In future work, we will conduct a formal user study for comparing our system with a baseline system in quantitative terms to evaluate the usability of our system. Additionally, we will conduct a case study with professional designers to verify the usefulness of our system in actual product design processes.

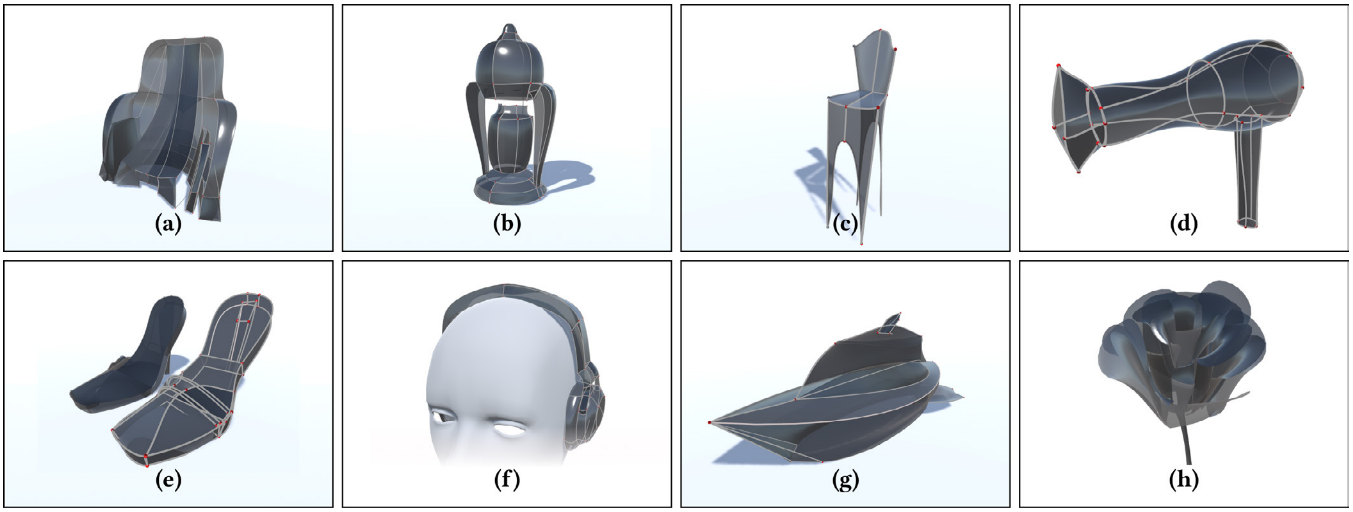

Figure 18: 3D product concepts designed by the participants during the pilot test. (a) Massage chair (P1, time taken: 51m 05s), (b) lamp (P1, time taken: 60m 03s), (c) bar stool (P2, time taken: 04m 19s), (d) hair dryer (P3, time taken: 17m 23s), (e) high heel shoes (P3, time taken: 48m 57s), (f) headphones (P4, time taken: 64m 06s), (g) yacht (P5, time taken: 52m 18s), and (h) rose (author, time taken: 15m 18s).

Acknowledgments

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References

[1] Adobe. 2016. Quill.
[2] Rahul Arora, Rubaiat Habib Kazi, Tovi Grossman, George Fitzmaurice, and Karan Singh. 2018. SymbiosisSketch: combining 2D & 3D sketching for designing detailed 3D objects in situ. In *Proc. CHI '18*. 1–15. https://doi.org/10.1145/3173574.3173759
[3] Rahul Arora, Rubaiat Habib Kazi, Fraser Anderson, Tovi Grossman, Karan Singh, and George Fitzmaurice. 2017. Experimental evaluation of sketching on surfaces in VR. In *Proc. CHI '17*. 5643–5654. https://doi.org/10.1145/3025453.3025474
[4] Seok-Hyung Bae, Takahiro Kobayash, Ryugo Kijima, and Won-Sup Kim. 2004. Tangible NURBS-curve manipulation techniques using graspable handles on a large display. In *Proc. UIST '04*. 81–90. https://doi.org/10.1145/1029632.1029646
[5] Ravin Balakrishnan, George Fitzmaurice, Gordon Kurtenbach, and William Buxton. 1999. Digital tape drawing. In *Proc. UIST '99*. 161–169. https://doi.org/10.1145/320719.322598
[6] Bruno R. De Araùjo, Géry Casiez, and Joaquim A. Jorge. 2012. Mockup builder: direct 3D modeling on and above the surface in a continuous interaction space. In *Proc. GI '12*. 173–180. https://doi.org/10.5555/2305276.2305305
[7] Tobias Drey, Jan Gugenheimer, Julian Karlbauer, Maximilian Milo, and Enrico Rukzio. 2020. VRSketchIn: exploring the design space of pen and tablet interaction for 3D sketching in virtual reality. In *Proc. CHI '20*. 1–14. https://doi.org/10.1145/3313831.3376628
[8] Google. 2016. TiltBrush.
[9] Tovi Grossman, Ravin Balakrishnan, Gordon Kurtenbach, George Fitzmaurice, Azam Khan, and Bill Buxton. 2001. Interaction techniques for 3D modeling on large displays. In *Proc. I3D '01*. 17–23. https://doi.org/10.1145/364338.364341
[10] Tovi Grossman, Ravin Balakrishnan, Gordon Kurtenbach, George Fitzmaurice, Azam Khan, and Bill Buxton. 2002. Creating principal 3D curves with digital tape drawing. In *Proc. CHI '02*. 121–128. https://doi.org/10.1145/503376.503398
[11] Yves Guiard. 1987. Asymmetric division of labor in human skilled bimanual action: the kinematic chain as a model. *Journal of Motor Behavior* 19, 4 (1987), 486–517. https://doi.org/10.1080/00222895.1987.10735426
[12] Devamardeep Hayatpur, Seongkook Heo, Haijun Xia, Wolfgang Stuerzlinger, and Daniel Wigdor. 2019. Plane, ray, and point: enabling precise spatial manipulations with shape constraints. In *Proc. UIST '19*. 1185–1195. https://doi.org/10.1145/3332165.3347916
[13] Bret Jackson and Daniel F. Keefe. 2016. Lift-Off: using reference imagery and freehand sketching to create 3D models in VR. *TVCG* 22, 4 (2016), 1442–1451. https://doi.org/10.1109/TVCG.2016.2518099
[14] Ying Jiang, Congyi Zhang, Hongbo Fu, Alberto Cannavò, Fabrizio Lamberti, Henry Y K Lau, and Wenping Wang. 2021. HandPainter - 3D sketching in VR with hand-based physical proxy. In *Proc. CHI '21*. Article 412, 13 pages. https://doi.org/10.1145/3411764.3445302
[15] Daniel F. Keefe, Daniel Acevedo Feliz, Tomer Moscovich, David H. Laidlaw, and Joseph J. LaViola. 2001. CavePainting: a fully immersive 3D artistic medium and interactive experience. In *Proc. I3D '01*. 85–93. https://doi.org/10.1145/364338.364370
[16] Daniel F. Keefe, Robert Zeleznik, and David Laidlaw. 2007. Drawing on air: input techniques for controlled 3D line illustration. *TVCG* 13, 5 (2007), 1067–1081. https://doi.org/10.1109/TVCG.2007.1060
[17] Hyosun Kim, Georgia Albuquerque, Sven Havemann, and Dieter W Fellner. 2005. Tangible 3D: hand gesture interaction for immersive 3D modeling. *IPT/EGVE* 2005, 2005 (2005), 191–199. https://doi.org/10.2312/EGVE/IPT_EGVE2005/191-199
[18] Kin Chung Kwan and Hongbo Fu. 2019. Mobi3DSketch: 3D sketching in mobile AR. In *Proc. CHI '19*. 1–11. https://doi.org/10.1145/3290605.3300406
[19] Kit Yung Lam, Lik-Hang Lee, and Pan Hui. 2022. 3DeformR: freehand 3D model editing in virtual environments considering head movements on mobile headsets. In *Proc. MMSys '22*. 52–61. https://doi.org/10.1145/3524273.3528180
[20] Celine Latulipe, Craig S. Kaplan, and Charles L. A. Clarke. 2005. Bimanual and unimanual image alignment: an evaluation of mouse-based techniques. In *Proc. UIST '05*. 123–131. https://doi.org/10.1145/1095034.1095057
[21] Sang-Hyun Lee, Taegyu Jin, Joon Hyub Lee, and Seok-Hyung Bae. 2022. WireSketch: bimanual interactions for 3D curve networks in VR. In *UIST '22 Adjunct*. Article 37, 3 pages. https://doi.org/10.1145/3526114.3558726
[22] Mayra D. Barrera Machuca, Paul Asente, Wolfgang Stuerzlinger, Jingwan Lu, and Byungmoon Kim. 2018. Multiplanes: assisted freehand VR sketching. In *Proc. SUI '18*. 36–47. https://doi.org/10.1145/3267782.3267786
[23] Mayra D. Barrera Machuca, Wolfgang Stuerzlinger, and Paul Asente. 2019. Smart3DGuides: making unconstrained immersive 3D drawing more accurate. In *Proc. VRST '19*. Article 37, 13 pages. https://doi.org/10.1145/3359996.3364254
[24] Tim McGraw, Esteban Garcia, and Drew Sumner. 2017. Interactive swept surface modeling in virtual reality with motion-tracked controllers. In *Proc. SBIM '17*. Article 4, 9 pages. https://doi.org/10.1145/3092907.3092908
[25] Brian P. Perles and Judy M. Vance. 2002. Interactive virtual tools for manipulating NURBS surfaces in a virtual environment. *Journal of Mechanical Design* 124, 2 (2002), 158–163. https://doi.org/10.1115/1.1464132
[26] Les Piegl and Wayne Tiller. 2012. *The NURBS Book*. Springer Science & Business Media.
[27] Steven Schkolne, Michael Pruett, and Peter Schröder. 2001. Surface drawing: creating organic 3D shapes with the hand and tangible tools. In *Proc. CHI '01*. 261–268. https://doi.org/10.1145/365024.365114
[28] Gravity Sketch. 2016. Gravity Sketch.
[29] Tijana Vuletic, Alex Duffy, Chris McTeague, Laura Hay, Ross Brisco, Gerard Campbell, and Madeleine Grealy. 2021. A novel user-based gesture vocabulary

for conceptual design. *International Journal of Human-Computer Studies* 150 (2021), 102609. https://doi.org/10.1016/j.ijhcs.2021.102609

[30] Gerold Wesche and Hans-Peter Seidel. 2001. FreeDrawer: a free-form sketching system on the responsive workbench. In *Proc. VRST '01*. 167–174. https://doi.org/10.1145/505008.505041

[31] Min Xin, Ehud Sharlin, and Mario Costa Sousa. 2008. Napkin sketch: handheld mixed reality 3D sketching. In *Proc. VRST '08*. 223–226. https://doi.org/10.1145/1450579.1450627

[32] Xinchi Xu, Yang Zhou, Bingchan Shao, Guihuan Feng, and Chun Yu. 2023. GestureSurface: VR sketching through assembling scaffold surface with non-dominant hand. *TVCG* 29, 5 (2023), 2499–2507. https://doi.org/10.1109/TVCG.2023.3247059

[33] T. P. Yeh and J. M. Vance. 1998. Applying virtual reality techniques to sensitivity-based structural shape design. *Journal of Mechanical Design* 120, 4 (1998), 612–619. https://doi.org/10.1115/1.2829323

[34] Emilie Yu, Rahul Arora, Tibor Stanko, J. Andreas Bærentzen, Karan Singh, and Adrien Bousseau. 2021. CASSIE: curve and surface sketching in immersive environments. In *Proc. CHI '21*. Article 190, 14 pages. https://doi.org/10.1145/3411764.3445158

[35] Xue Yu, Stephen DiVerdi, Akshay Sharma, and Yotam Gingold. 2021. ScaffoldSketch: accurate industrial design drawing in VR. In *Proc. UIST '21*. 372–384. https://doi.org/10.1145/3472749.3474756