Bending Form in Extended Reality: A Gesture-Based Workflow of Chair Design and Fabrication

Abstract

Methods of integrating Extended Reality (XR) technology into the fabrication and assembly process are an intensively studied topic in the fields of Human-computer Interaction and Digital Fabrication. However, existing research primarily focuses on fabrication processes rather than breaking the limitations of current computer-aided design tools. XR technology can offer an immersive environment where designers can intuitively interact with 3D models. This paper pioneers the integration of XR not only for fabrication but also for the intuitive design process. The limitation of nowadays computer-aided design tools is its restriction to manipulating geometries in only 2D screen space, or the unintuitive predefined parameters and algorithms. To address this issue, we introduce a gesture-based intuitive design workflow. This workflow features three design modes: the “Free Draw” mode, the “Polyline Fillet” mode, and the “Spline Curve” mode. Through the design and fabrication process of two bending-form chairs, we demonstrate the implementation of mathematical and geometrical manipulation algorithms on spatial computation platform using a head-mounted display device. Besides, this research also elaborates on how to convert a spline curve to a format suitable for bending, as well as how to implement the steel tube bending simulation to prevent collisions with the environment during actual bending. The results of this research illustrate the entire design and fabrication process, highlighting the potential of XR to enhance the design process through a comparison between intuitive and traditional design methods, and paving the way of further development of the design and fabrication tools on spatial computation platforms.

Keywords: *Applied Research, scale S, Extended Reality, Gesture-Based Design and Fabrication, Steel Tube Bending*

1. Introduction

The style and appearance of pavilions, landscapes, and architectures in the built environment are in a constant state of “Designing Change”, mirroring the dynamic shifts in trends and preferences. This evolutionary process is closely intertwined with the continuous advancements in design tools and technologies. In the past, architects relied on 2D drawing on papers to explore design possibilities. Over the past three decades, the emergence of computational design tools and automated fabrication technologies has ushered in a new era of complexity and abundance in the design paradigm (Robertson and Radcliffe 2009). However, only until recently with the introduction of Extended Reality (XR) technology that the limitations of traditional 2D screens, mouse, and keyboard interfaces were transcended. XR technology enables designers to directly design in 3D space, allowing them to create and visualize designs in real-time at 1-to-1 scale, thereby revolutionizing the design process (Figure 1).

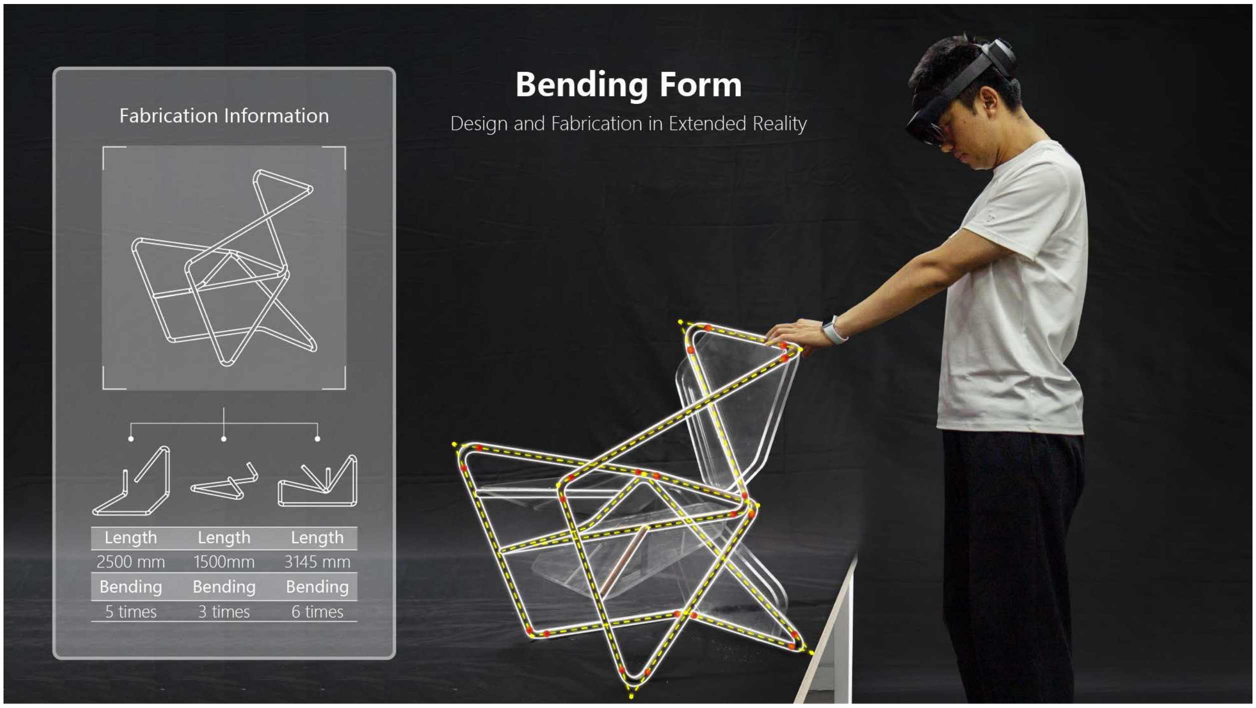

Figure 1. Bending Form Design and Fabrication in Extended Reality.

XR technology has become increasingly prevalent in various applications within the fields of architecture, engineering, and construction. By overlaying virtual images onto physical environments, it aids builders in completing precise manual fabrication and assembly tasks. Its versatility is evident in a multitude of practical applications, ranging from conventional material construction tasks such as bricklaying (Jahn et al. 2020) and fabricating glued laminated timber beams (Kyaw et al. 2023), to more unconventional projects like freeform block construction (Sun et al. 2018) and bamboo art installations (Goepel and Crolla 2020). Additionally, XR technology facilitates intuitive control of robotic arms for timber prefabrication processes (Kyjanek et al. 2019), leveraging the ability of human decisions to enable adaptation to non-linear construction workflows and unforeseen events (Mitterberger et al. 2022; Yang et al. 2022; Wang, Lin, and Sun 2023). Furthermore, it facilitates task distribution and assembly guidance for collaborative multi-user participation (Atanasova et al. 2023).

However, these papers mainly focus on enhancing the fabrication and assembly processes rather than breaking the limitations of current computer-aided design tools. Nowadays design tools are restricted to manipulating geometries using transform manipulator along three axes or three planes within the screen space (Figure 2b). Alternatively, designs may be governed by predefined parameters and algorithms that lack intuitiveness and are challenging to adjust when unforeseen logic-related conditions arise (Figure 2c). XR technology can offer an immersive environment where designers can intuitively interact with 3D models. In order to unleash the full potential of

XR, this research proposes a software framework for gesture-based workflow (Figure 2a) integration on a spatial computation platform, to not only facilitate the fabrication process, but also enhance the intuitive design process.

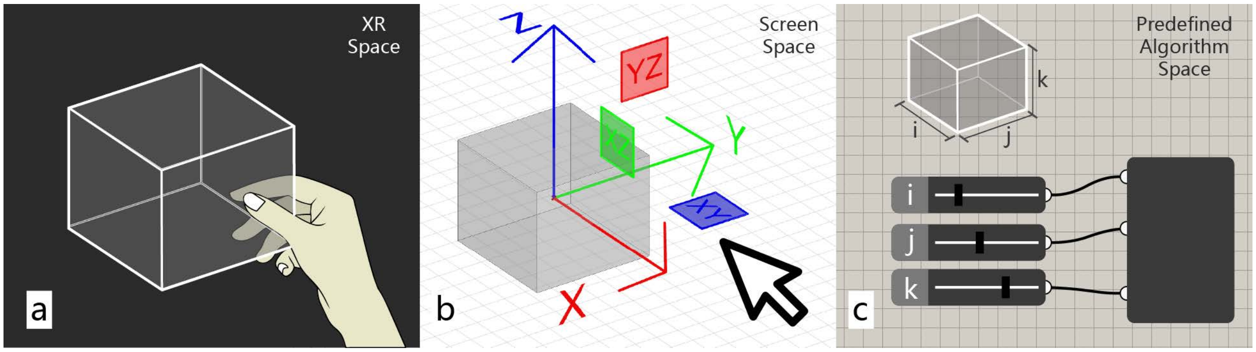

Figure 2. The Comparison Between Three Design Methods: (a) Gesture-based design in XR space, (b) Mouse-based design in screen space, (c) Parameter-based design in predefined algorithm space.

There are three distinct gesture-based design modes: "Free Draw", "Polyline Fillet", and "Spline Curve" in this software. Additionally, it enables the alignment of virtual models with the physical world using QR Code. Real-time environmental scanning is also integrated to offer simulation capabilities for steel tube bending tasks, preventing potential collisions. As a proof of the concept, the design and fabrication processes of two bending-form chairs are presented. Designers engage with the software by initially conducting a case study of physical and virtual chair models using the "Free Draw" mode. Subsequently, they utilize the other two modes to refine the design before employing the software to execute bending simulations and fabrication processes.

2. State of the Art

This study follows a lineage of research exploring the workflow of bending form of linear elements, such as hollow steel tube or solid-core rod. These precedents demonstrate that different fabrication methods to realize bending forms. In *Robotic Rod-bending* and *The Novel Stones of Venice*, a 6-axis industrial robot is used to bend the solid-core rod and welding is used as a primary method of joinery (MacDowell and Tomova 2011; Maxwell, Pigram, and McGee 2013). In *Making in Mixed Reality*, XR technology is used to obtain scanned environment models for simulating the bending process to prevent collisions. Additionally, they overlay virtual tube models onto the physical steel tubes to aid users in identifying the correct bending position and angle thus facilitating the bending process (Jahn, Newnham and Beanland 2018). In *Augmented Reality Assisted Robotic Tube Bending*, XR technology is integrated into the robotic bending and manual assembly workflow to improve the accuracy (Huang and Spaw 2023).

There are also some studies focusing on integrating XR technology into the design process. In *Augmented Masonry Design*, slider components from the parameter-based design method are incorporated into the XR design space to control the radius, brick numbers and wall height when designing a brick wall. Additionally, the author leverages the gesture recognition algorithms to provide an intuitive way to draw the basic spline curves of brick walls (Song, Agkathidis and Koeck 2022). In *Interactive Robotic Plastering*, a projection-based augmented reality design method reads the human input data from the position of a controller and its distance from the wall, then translate this data in real time to implement a plastering work (Mitterberger et al. 2022). Our research employs XR technology with a head-mounted display device and a manual steel tube bending machine to complete the design and fabrication processes of two bending-form chairs.

3. **Methods**

This research explores a gesture-based workflow integrated into both design and fabrication processes, working seamlessly with the common 3D modeling software Rhinoceros. Real-time calculations of body behavioral data, such as the positions and orientations of the head, eye gaze point, and hand joints, are performed by the Microsoft HoloLens 2, a head-mounted display device. The body behavioral and geometrical data are transmitted bidirectionally between the head-mounted display device and Rhinoceros using the Rhino Inside Unity package. A QR Code is used to align the coordinate system in the virtual world with the physical world. The environment mesh model is scanned using the Simultaneous Localization and Mapping (SLAM) algorithm provided by the head-mounted display device. This environment model is then utilized to simulate the bending process, effectively preventing collision issues. A series of gestures are configured to enhance the intuitive design workflow. The “pinch” gesture is recognized when the distance between the user’s index fingertip and thumb fingertip is less than one-quarter of the length of the user’s index finger, a measurement that varies from one individual to another (Figure 3).

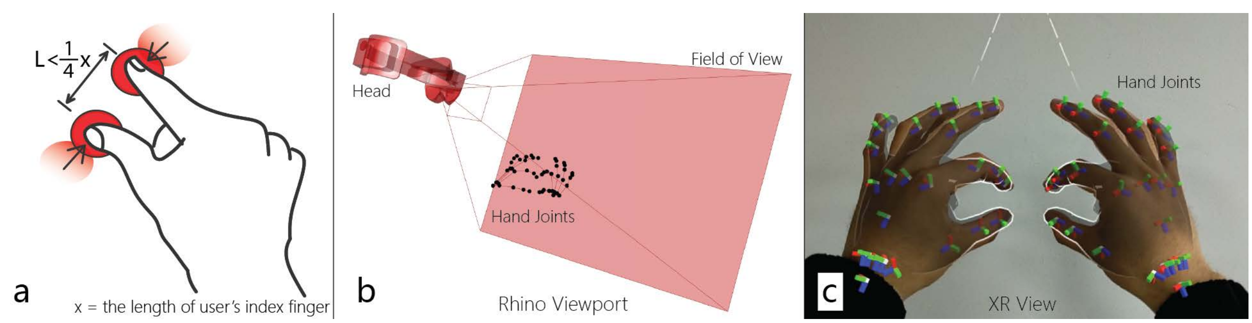

Figure 3. Pinch Gesture Recognition: (a) Pinch gesture recognition distance threshold, (b) Pinch gesture in Rhino viewport, (c) Pinch gesture in XR view.

The "pinch" gesture, combined with the "drag" gesture and 3DUI, facilitates the bending form design and fabrication workflow across four stages: the case study stage, design stage, simulation stage, and fabrication stage (Figure 4). For instance, during the case study stage, the "pinch and drag" gesture forms the basis of the "Free Draw" mode for constructing a mesh pipe in real-time. In the design stage, the "pinch" gesture serves as the basis of the "Polyline Fillet" mode, enabling the recording of point positions and subsequent drawing of a polyline, awaiting arc fillet operations. Additionally, the "pinch and drag" gesture allows for adjusting the positions of previously drawn points, deleting them, or modifying the fillet radius parameter. In another instance, the "pinch" gesture forms the foundation of the "Spline Curve" mode, facilitating the creation and adjustment of spline curves, including point positions, control handles, and deletion of previously created points. In the simulation stage, the "pinch" gesture, in conjunction with 3DUI, toggles the display of the scanned environment model, allowing users to verify areas for collision. It also facilitates switching between current and previous tubes. During the fabrication stage, the "pinch" gesture, also combined with 3DUI, toggles between bending instructions, transitioning to the next or previous steel tube.

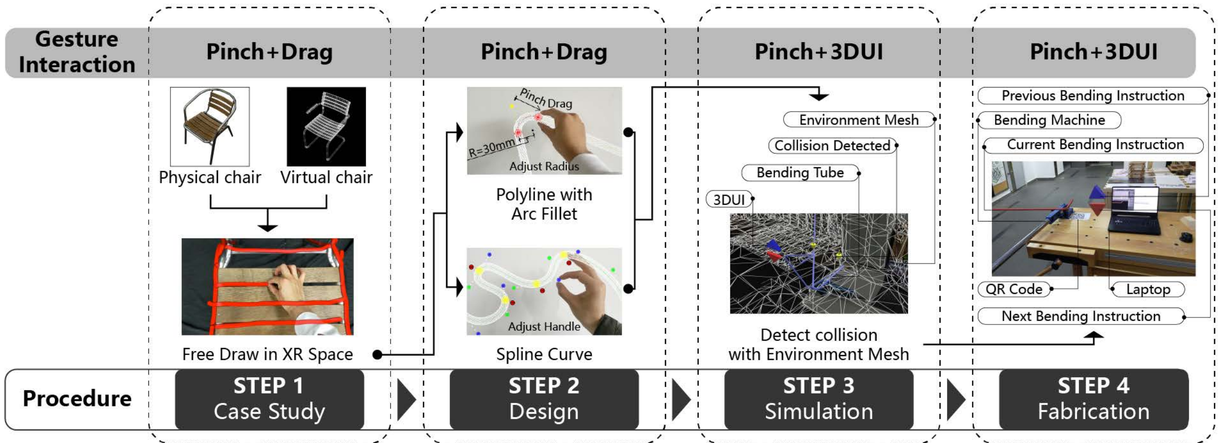

Figure 4. Overall Gesture-Based Workflow of Bending Form in Extended Reality

3.1. Case study with "Free Draw" mode

Before initiating chair design, designers utilize XR technology to conduct case studies using the "pinch" gesture, "drag" gesture, and the "Free Draw" mode. The hand menu UI of the "Free Draw" mode is meticulously designed to appear on various parts of the hand, such as fingertips, palm, and wrist. A floating white bar will appear at the right side of the palm when the HoloLens sensors detect the left hand's palm. All menu contents will appear after the floating bar is pinched and dragged out (Figure 5a). The hand menu comprises five sections: the first, located at the right side of the palm, is used to switch between three different drawing modes with "Free Draw" mode currently selected. The second, located at the center of the palm, serves as a color palette for adjusting the color of the current drawing stroke, it will remember four colors which are used most recently and display them as separately as quick accessible colors. The third part is four spheres with different radius corresponding to the size of the drawing stroke, from the thumb fingertip to the ring fingertip its radius changes from 20mm to 8mm. The fourth part is a switch on the wrist for toggling between "Create", "Erase", and "MRS" (Move, Rotate, Scale) modes. The fifth part is a button near the root of the thumb for toggling between erase stroke partially and entirely.

When the "Create" button is activated, designer can pinch and drag in the air to generate new mesh pipes based on the position of the pinch gesture. The new point is recorded only if its distance from the previous point exceeds 8mm, preventing excessive point accumulation which could affect the performance of the software (Figure 5b). If the "Erase" button is activated, it automatically switches to "Partial Erase" mode. When the user pinches and drags in this mode, an invisible mesh pipe is drawn to detect collisions with existing drawing strokes. If a collision is detected, the affected portion of the existing stroke will be removed (Figure 5c). Alternatively, toggling to "Erase Entire" mode removes the entire existing stroke upon collision detection (Figure 5d). If the "Move, Rotate, Scale" button is pressed, the user can manipulate the mesh pipe intuitively using pinch and drag gestures (Figure 5e).

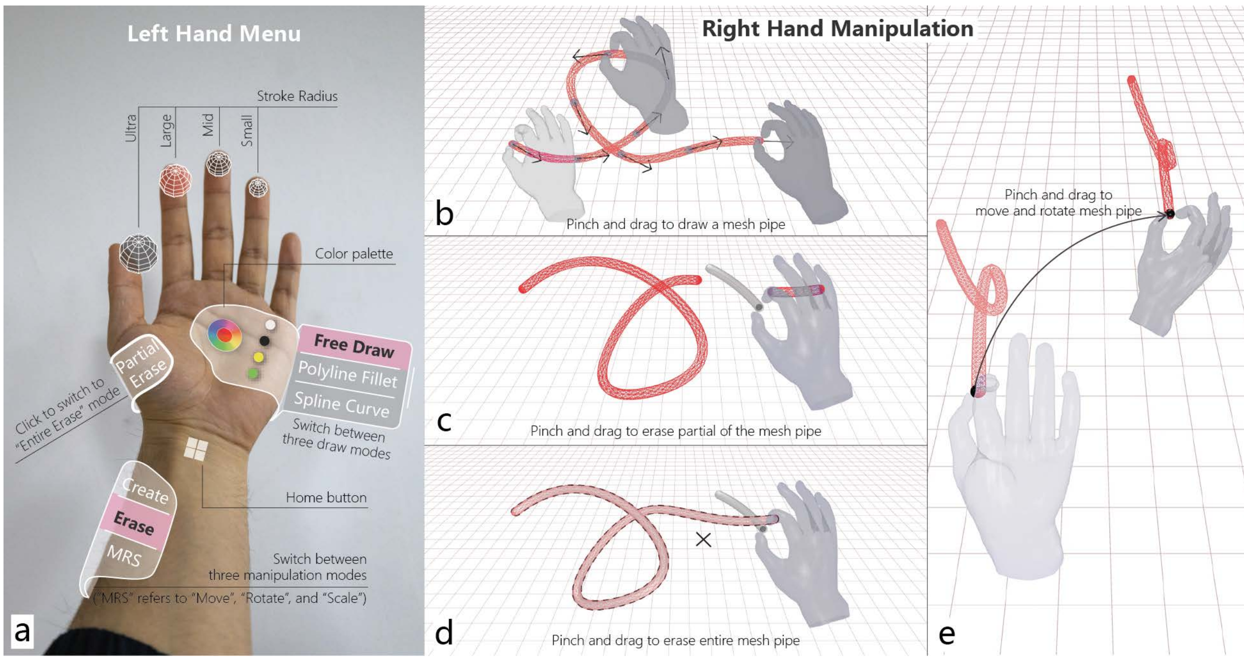

Figure 5. Free Draw Mode: (a) Hand Menu UI in XR space, (b) Create new curve, (c) Erase curve partially, (d) Erase curve entirely, (e) Move and rotate curve.

Both physical and virtual chairs can be seamlessly integrated into the XR space at 1-to-1 scale. This enables users to explore the connection details of steel tubes with various materials such as wood plates, plastic, or fabric. For clarity, we present the case study results of two chairs, one representing a physical chair (Figure 6d) and the other a virtual chair (Figure 6e). Besides, the QR code is used to sync the coordinate system between the XR space and the real world (Figure 6g), and the designer's view and the real-time pose of head and hand-joints are synced to the big screen (Figure 6a).

While we demonstrate on two chairs for illustrative purposes, our study encompassed approximately twenty chairs to find out the average length of steel tubes used. For instance, the steel tube length of the chair depicted in Figure 5d measures 6.3 meters, whereas the chair shown in Figure 5e has a steel tube length of 3.16 meters. These observations provide valuable insights into the required tube length and the visual impact, indicating whether the chair appears light or heavy. This analysis offers a preliminary estimation of the length of tubing necessary to ensure the rationality of the chair design.

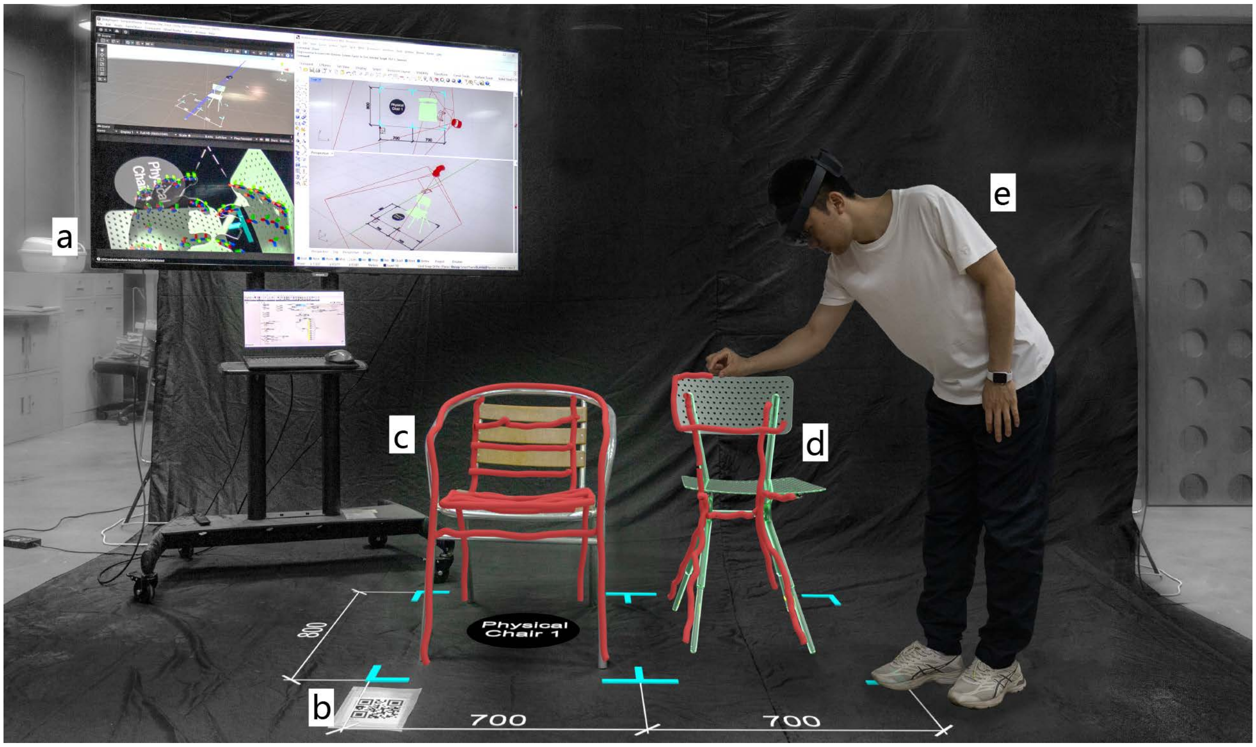

Figure 6. Gesture-Based Extended Reality Case Study Workspace: (a) Designer's view and the real-time pose of head and hand-joints, (b) QR-Code used to align the virtual model with physical world, (c) Physical chair with sketch result, (d) Virtual chair with sketch result, (e) Designer with head-mounted display device.

3.2. Bending form design with "Polyline Fillet" mode

Since steel tube materials are initially straight and require bending to assume spatial shapes, bending machines—whether CNC-controlled or manual tools—typically utilize a round-shaped disc to bend the steel tube at a specific radius. Therefore, the "Polyline Fillet" mode is specifically designed to align with this fabrication method. To switch to this mode, select the "Polyline Fillet" option on the hand menu (Figure 7a). The "Create" button is activated by default for users to create polyline. The system records the average position between the thumb fingertip and index fingertip upon recognizing the pinch gesture, subsequently drawing a polyline. Users can preview new polyline segments while pinching, with the segment being finalized upon releasing of the pinch gesture. If users need to draw additional polylines, they must toggle between the "Create" button and another manipulation mode before continuing to draw new polylines. The main distinction in the menu compared to the previous "Free Draw" mode is the "Edit" section. Pressing the "Edit" button automatically activates the "Edit Fillet Radius or Delete Point" option. Users can then use pinch and drag gestures to adjust the fillet radius or pinch on the red circle with a dash in the center icon to delete a point from the polyline (Figure 7b). To adjust the position of a point on the polyline, users need to switch to the "Edit Polyline" option within the hand menu (Figure 7a).

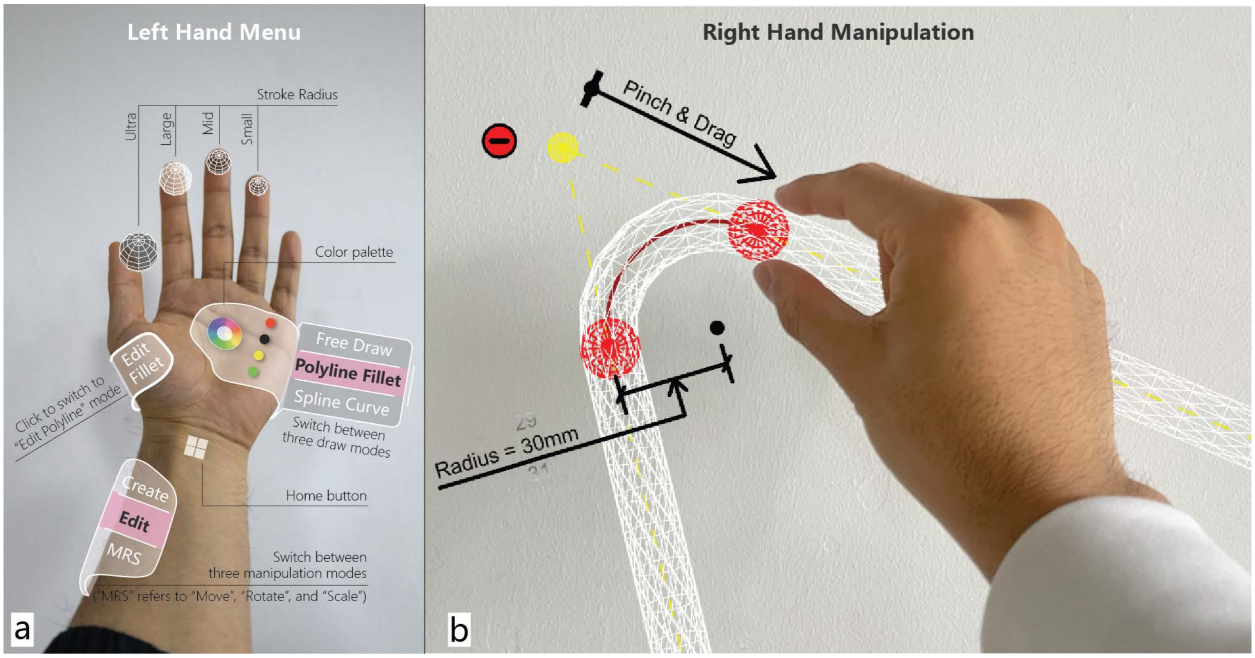

Figure 7. Polyline Fillet Mode: (a) Hand Menu UI in XR space, (b) Pinch and drag to edit the fillet radius of polyline.

The design strategy for the first chair focuses on its mobility and rotatability to accommodate various sitting postures. This approach allows for the adjustment of different sitting surface heights and back surface angles, catering to the diverse needs of users. Leveraging XR technology, 1-to-1 scale human models assume different postures within the XR space, serving as references during the design process. For instance, models with adults sitting upright, adults reclining at 135 degrees, and children sitting upright offer guidance to designers in determining the optimal chair height. Additionally, the pinch gesture enables designers to effortlessly adjust the position of points on the polylines, further facilitating the design refinement process (Figure 8).

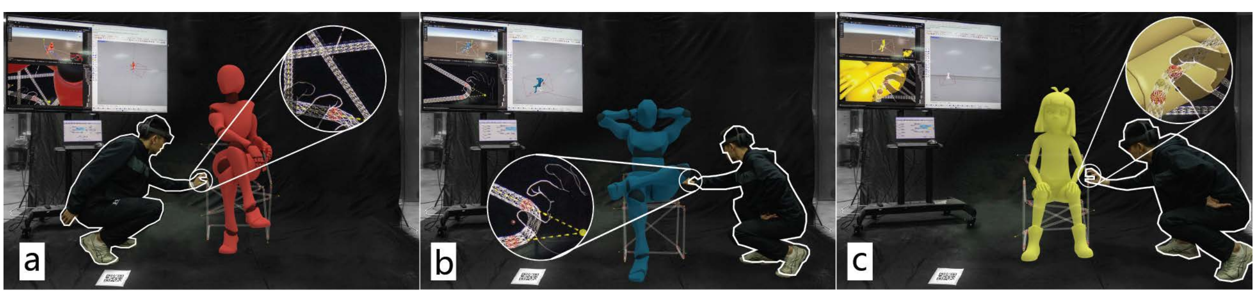

Figure 8. Design with 1-to-1 Scale Human Model and "Polyline Fillet" Mode: (a) Design with adult sitting straightly, (b) Design with adult sitting causally, (c) Design with child sitting straightly.

3.3. Bending form design with "Spline Curve" mode

Freeform design is becoming more and more popular, and it requires the precise description of complex shapes using spline curves. Therefore, the "Spline Curve" mode has been developed to meet this demand. Users can switch to this mode by selecting the third button on the right side of the hand menu (Figure 9a). To create spline curves, users can press the "Create" button. The system will then record the pinch gesture position and automatically generate a control handle. Pressing the "Edit" button reveals control handles, allowing users to intuitively adjust their positions using pinch and drag gestures. Additionally, users can delete points by pinching the red icon (Figure 9b).

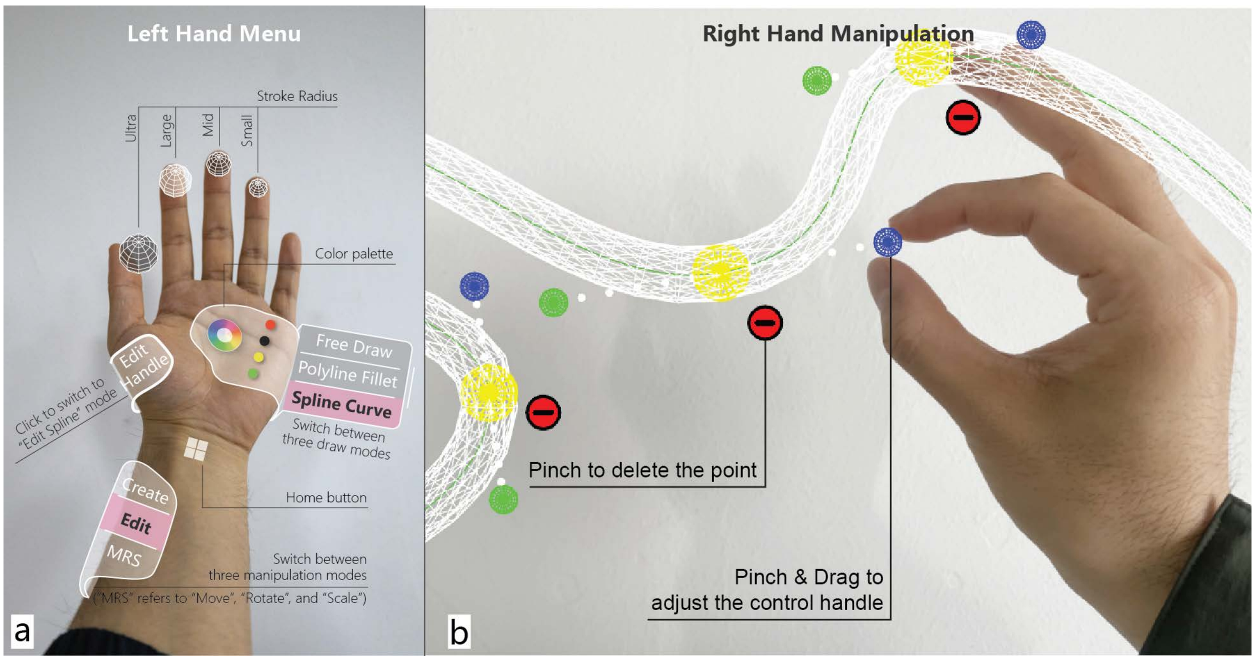

Figure 9. Spline Curve Mode: (a) Hand Menu UI in XR space, (b) Edit the control handle of spline curve.

The second chair also aims to provide a comfortable experience for various postures, including sitting and lying posture. Given the unique requirements of the lying posture, which demands a shape that conforms to the curves of the human body, the "Spline Curve" mode is well-suited for this task. To facilitate the design process, 1-to-1 scale virtual human models are incorporated into the XR space as references. During the design process, designer should initially raise their left hand and pull out the floating white bar on the right side of the palm to reveal the complete hand menu. When the "Create" button is pressed, the designer can pinch in the air to create a new point for the spline curve. To start a new spline curve, the designer needs to switch to another button and then back to "Create". When the "Edit" button is pressed, the designer can toggle between "Edit Handle" and "Edit Spline" to adjust the position of the control handles, delete points on the spline curve, or adjust the position of the points on the spline curve. When "MRS" button is pressed, designer can pinch and drag to manipulate the entire spline curve (Figure 10).

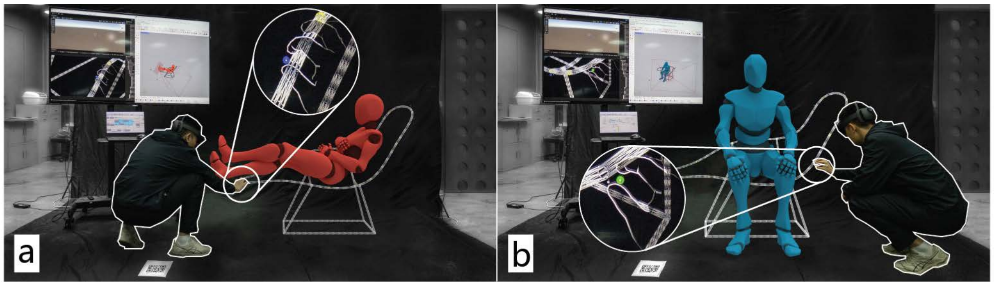

Figure 10. Design with 1-to-1 Scale Human Model and “Spline Curve” Mode: (a) Design with adult lying casually, (b) Design with adult sitting straightly.

3.4. Bending simulation

The bending simulation algorithm requires the input geometry data to be straight lines with arc fillets. Therefore, the spline curve of the second chair needs to be optimized for the bending simulation. The first step in the optimization process is to rebuild the spline curve into a polyline with a certain number of points. Next, each corner of the polyline is filleted, and the average deviation between the original spline curve and the optimized curve is calculated. The curve is considered ready for simulation when the average deviation is less than 3mm (Figure 11).

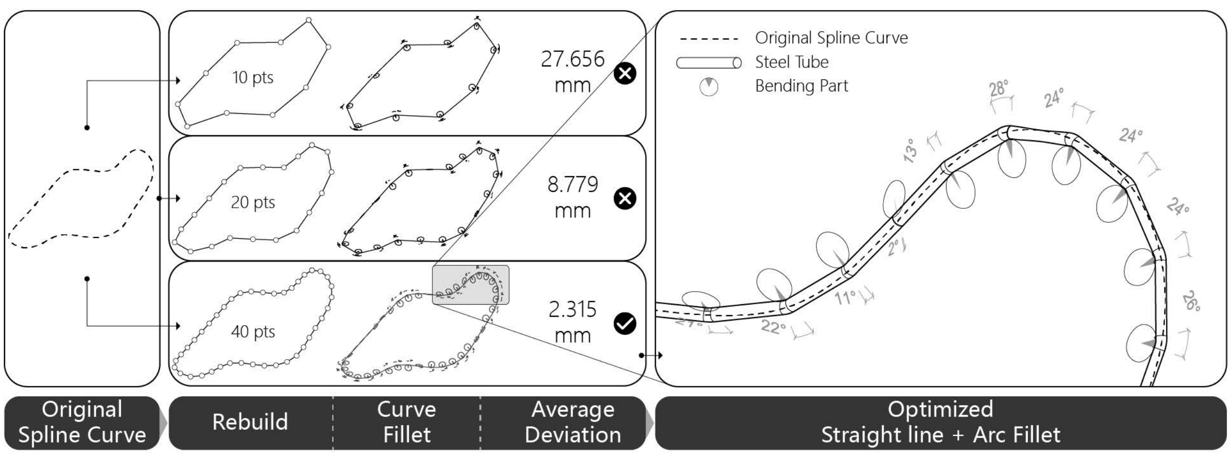

Figure 11. Optimization of spline curve.

The objective of the bending simulation is to ensure there are no collisions between the steel tube and the environment or the steel tube itself, thus verifying that the bending fabrication process can be conducted successfully. The environment mesh model is captured by HoloLens and sent via Wi-Fi to the laptop in real-time. Collisions are tested in each frame of the simulation process.

The simulation algorithm consists of two parts: parameter extraction and the simulation process. In the first part, a polyline is imported, and the straight lines and arcs from the filleted polyline are extracted. Parameters for each bending operation are then calculated from these segments. Each arc represents a bending operation, and each bending operation consists of three parameters: straight-line length, rotation angle, and bending angle (Figure 12). The straight-line length (L) is calculated by measuring the length of the straight segment before the bending operation arc. The bending angle (A) is determined by measuring the angle of the arc. The rotation angle (R) is calculated by projecting the second previous straight segment and the subsequent straight segment onto planes perpendicular to the straight segment before the bending arc.

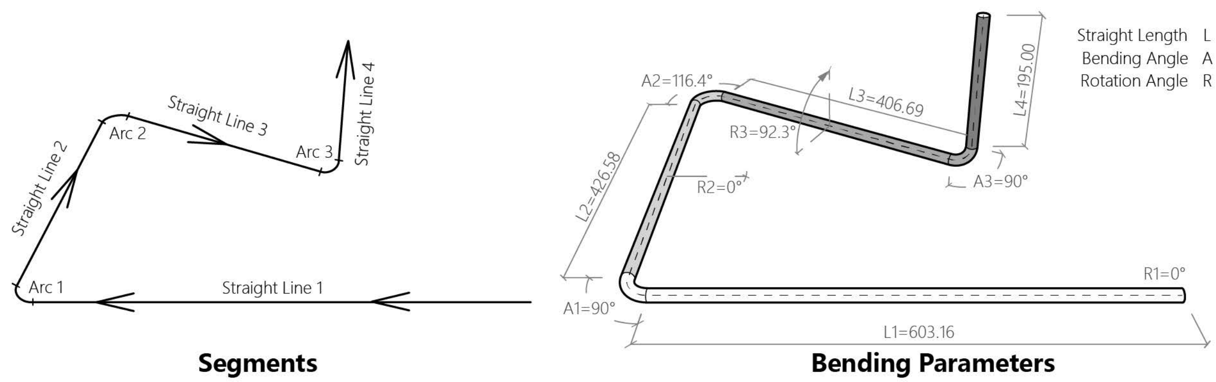

Figure 12. Bending Parameters Extraction.

In the second part, a predefined algorithm is developed to execute the bending simulation process. Primarily, it comprises a loop initialized with all the parameters extracted from the first step and a straight line representing the steel tube before bending. Additionally, the number of arc segments determines the total loop count.

Within the loop, there are four main steps. Firstly, the steel tube is moved according to the straight-line length parameter. Secondly, it undergoes rotation along the feeding axis of the manual bending machine based on the rotation angle parameter. Thirdly, it is divided at the bending start point, and the latter part of the split result is bent based on the bending angle parameter. Subsequently, the two parts are joined as a whole. Finally, the entire curve is rotated back based on the bending angle parameter. Additionally, a Python script and a trigger component automate the simulation process. As the iteration index changes, the Python script outputs a decimal number ranging from 0 to 1 to control the four steps. This process continues iteratively until all bending operations are simulated.

During the bending simulation process, user should pinch on the 3DUI to switch the iteration index (Figure 13a), and a yellow arrow will be displayed above the collision position if a collision is detected (Figure 13c and 13d). The seams of the closed steel tube should be adjusted or the larger components should be divided into smaller parts to avoid collision situations. After many times of adjustments and simulations, the final bending parts and parameters are determined to ensure that there wouldn’t be problem in the actual bending fabrication process. Take a steel tube with six bending operations as an example (Table 1), a regular pattern could be found that the first rotation angle will always be zero and the length of the last arc segment isn’t needed.

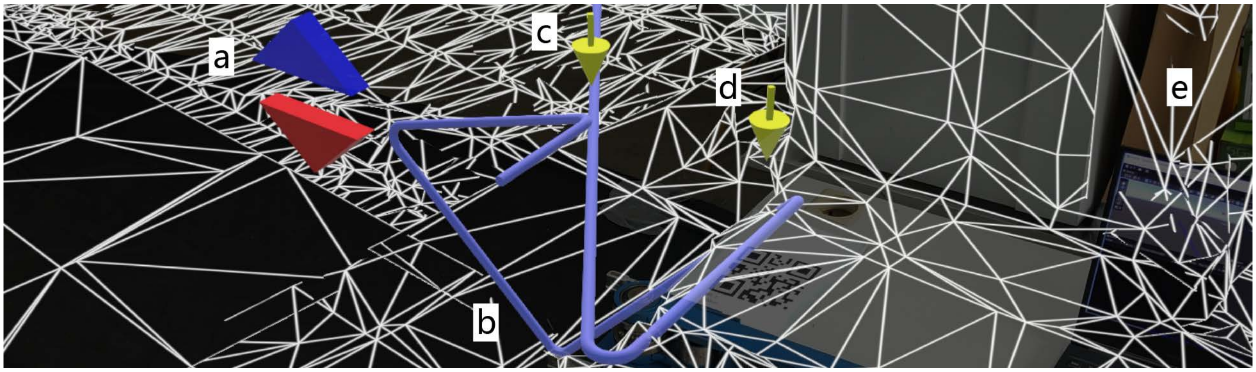

Figure 13. Bending Simulation in XR view: (a) 3DUI to change current bending simulation operation index, (b) A steel tube, (c) Self-collision detected, (d) Tube-environment collision detected, (e) An environment mesh model.

Table 1: Bending parameters of a typical steel tube with six operations

Operation Index	Straight-line Length (L) / mm	Rotation Angle (R) / °	Bending Angle (A) / °
1	195.00	0.0	90.0
2	406.68	270.0	118.7
3	426.58	0.0	90.0
4	603.15	90.0	90.0
5	390.00	312.5	144.8
6	499.14	149.1	111.7

3.5. Bending fabrication

The manual bending machine used in this research is specifically designed for steel tubes with a 16mm outer diameter and a 30mm bending radius. It should be secured to a heavy operation table to ensure a smooth bending process (Figure 14a). A QR code is used to align the virtual models with the real-world coordinate system, and it should be carefully attached to the table to prevent systematic drift deviations (Figure 14c).

The program used in the fabrication process is the same as the one used in the bending simulation process. The only difference is that collision detection is no longer calculated in each frame, resulting in better performance. The program is written in Grasshopper and runs with Rhino Inside Unity (Figure 14e). The rendering contents are streamed from the laptop to HoloLens via a Wi-Fi connection. Users can pinch on the 3DUI to switch the current bending fabrication instruction to the previous one or the next one (Figure 14d). The actual steel tube should be bent according to the virtual image overlaid instruction to achieve the correct bending angle (Figure 15).

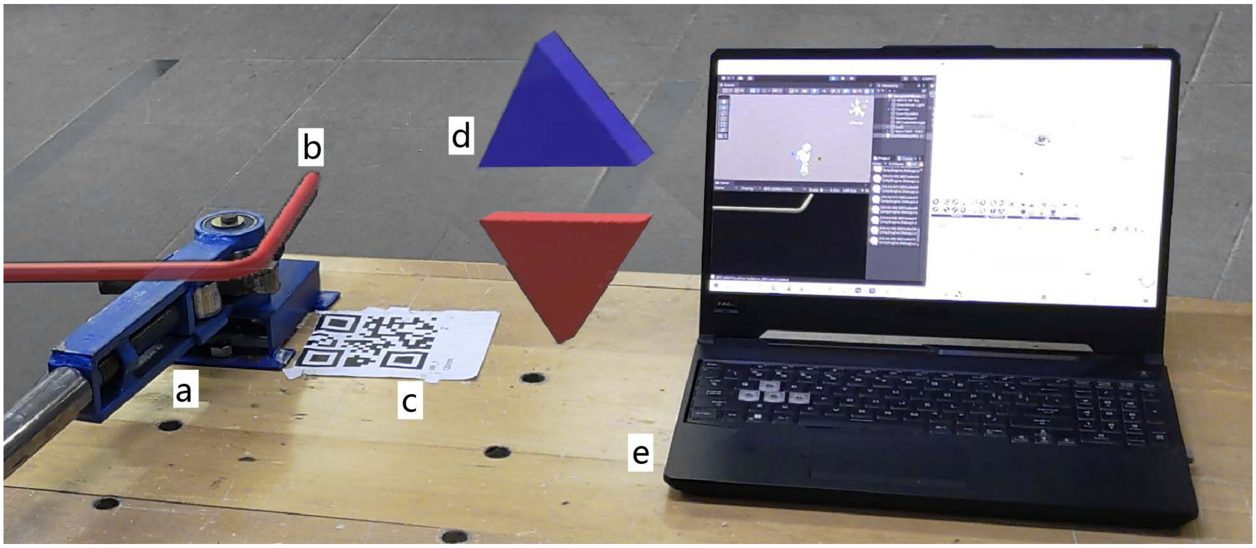

Figure 14. Bending Fabrication in XR View: (a) A manual bending machine, (b) A steel tube with virtual model overlaid, (c) QR code, (d) 3DUI to switch current bending tube instruction, (e) A laptop connected with HoloLens.

Figure 15. Bending Fabrication Process.

4. Results and Discussion

Following the workflow above, the three gesture-based drawing modes, “Free Draw”, “Polyline Fillet”, and “Spline Curve”, proved effective in different stages of chair design. In the “Free Draw” mode, designers could rapidly sketch on physical and virtual chairs at a 1-to-1 scale to conduct case study work, enabling them to learn about the basic properties of numerous high-quality chairs and prepare effectively for the design stage. Combined with 1-to-1 scale human models in different postures, the "Polyline Fillet" and "Spline Curve" modes provide designers with an intuitive way to precisely and easily adjust the positions of points on the chair shape.

After utilizing SLAM technology provided by XR devices to capture the environment model for bending simulation work and to prevent potential collision issues, the total length of 7145 mm steel tubing required for the Polyline Fillet Chair, with 14 bending operations, was divided into three parts: 3145 mm with six bending operations, 1500 mm with three bending operations, and 2500 mm with five bending operations. Similarly, the total length of 4177 mm steel tubing required for the Spline Curve Chair, with 40 bending operations, was divided into three parts: 1567 mm with 15 bending operations, 1358 mm with 13 bending operations, and 1252 mm with 12 bending operations (Figure 16). Thanks to the bending simulation, the actual bending operation was conducted safely with the assistance of the overlaid tube XR guidance.

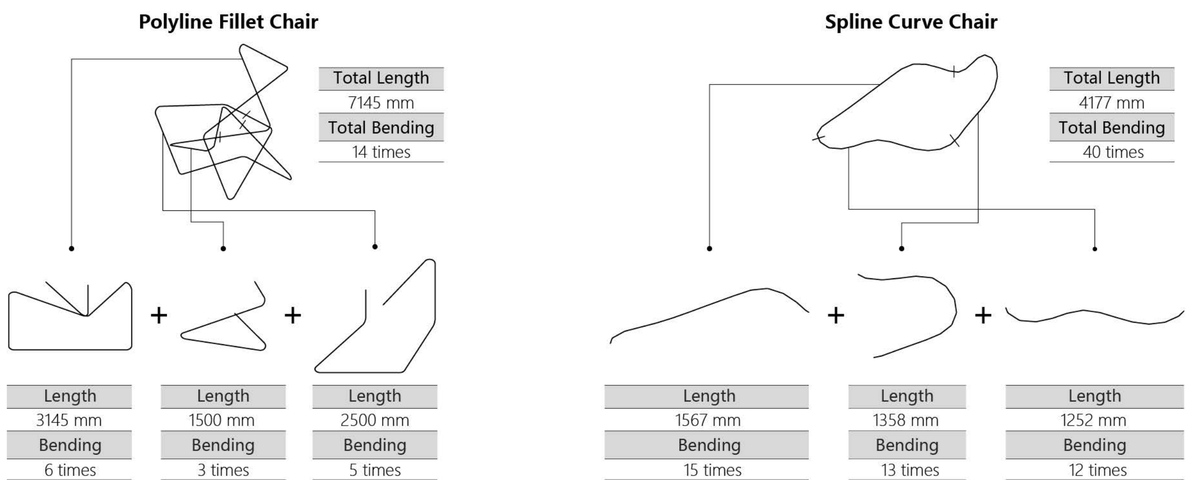

Figure 16. Segmented Parts for Bending Fabrication.

5. Conclusion

In contrast to prior research, this paper showcases the potential of a gesture-based workflow to streamline not only the fabrication but also the design process, focusing specifically on bending form design (Figure 17). The three gesture-based modes are used in the case study and the design stage, the QR code pose estimation and SLAM algorithm are used to empower the bending simulation and fabrication process. These modes, algorithms, and their corresponding UIs are proposed as an exploration of the innovative design tool on the spatial computation platform, demonstrating the viability of XR technology. Having transitioned from the era of designing with 2D drawing on papers to the era of designing with 2D screens, we are now entering an era of designing on the intuitive spatial computation platforms. We can manipulate designs with our hands in an intuitive way and experience them at a 1-to-1 scale.

While this study highlights several strengths, there are also areas for improvement. Firstly, this research primarily focuses on bending form design, which represents just one among many design possibilities. Moreover, the study's emphasis on chairs which are relatively small in size. Secondly, the sample size of testers in this research is not big enough, comprising only two people. Additionally, there is limited discussion regarding user feedback and the evaluation of user experience.

Future work will focus on refining the workflow to accommodate a broader range of design styles and testing the feasibility of this gesture-based approach in large-scale design scenarios, such as interior and building design. Additionally, future research should involve a larger group of testers to conduct a comprehensive evaluation of user experience. The overarching goal is to highlight and enhance the unique strengths of humans in the automation era, providing designers with an immersive experience throughout the design, fabrication, and assembly processes, ultimately leading to a better future of human-computer interaction.

Figure 17. Two Bending Form Chairs Finished with Gesture-Based Workflow in XR

References

B.F. Robertson, D.F. Radcliffe. 2009. "Impact of CAD Tools on Creative Problem Solving in Engineering Design." *Computer-Aided Design* 41(3): 136–146.

Gwyllim Jahn, Cameron Newnham, Nick Van Den Berg, Melissa Iraheta, and Jackson Wells. 2020. "Holographic Construction." In *Impact: Design With All Senses*, ed. C. Gengnagel, O. Baverel, J. Burry, M. R. Thomsen, and S. Weinzierl, 314–324. Berlin: DMS.

Alexander Htet Kyaw, Arvin HaoCheng Xu, Gwyllim Jahn, Nick Van Den Berg, Cameron Newnham, and Sasa Zivkovic. 2023. "Augmented Reality for High Precision Fabrication of Glued Laminated Timber Beams." *Automation in Construction* 152 (August): 104912.

Chengyu Sun, Zhaohua Zheng, Yuze Wang, and Tongyu Sun. 2018. "A Freeform Building Process with High Onsite Flexibility and Acceptable Accumulative Error." In *Proceedings of the 38th Annual Conference of the Association for Computer-Aided Design in Architecture (ACADIA)*, 82-87. Mexico City: ACADIA.

Garvin Goepel and Kristof Crolla. 2020. "Augmented Reality-Based Collaboration - ARgan, a Bamboo Art Installation Case Study." In *Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference - Volume 2*, ed. D. Holzer, W. Nakapan, A. Gloaba and I. Koh. 313-322. Bangkok, Thailand: CAADRIA.

Ondrej Kyjanek, Bahar Al Bahar, Lauren Vasey, Benedikt Wannemacher, and Achim Menges. 2019. "Implementation of an Augmented Reality AR Workflow for Human Robot Collaboration in Timber Prefabrication." In *Proceedings of the 36th ISARC*, 1223-1230. Banff, Canada: ISARC.

Daniela Mitterberger, Lidia Atanasova, Kathrin Dörfler, Fabio Gramazio, and Matthias Kohler. 2022. "Tie a Knot: Human–Robot Cooperative Workflow for Assembling Wooden Structures Using Rope Joints." *Construction Robotics* 6 (3–4): 277–92.

Xiliu Yang, Felix Amtsberg, Lior Skoury, Hans Jakob Wagner, and Achim Menges. 2022. "Vizor, Facilitating Cyber-Physical Workflows in Prefabrication through Augmented Reality." In *Proceedings of the 27th CAADRIA Conference, Volume 2*, 141–50. Sydney: CAADRIA.

Sining Wang, Dandan Lin, and Lujie Sun. 2023. "Human-Cyber-Physical System for Post-Digital Design and Construction of Lightweight Timber Structures." *Automation in Construction* 154 (October): 105033.

Lidia Atanasova, Begüm Saral, Ema Krakovská, Joel Schmuck, Sebastian Dietrich, Fadri Furrer, Timothy Sandy, Pierluigi D'Acunto, Kathrin Dörfler. 2023. "Collective AR-Assisted Assembly of Interlocking Structures." In: *Towards Radical Regeneration,* ed. C. Gengnagel, O. Baverel, G. Betti, M. Popescu, M.R. Thomsen, J. Wurm. Berlin: DMS.

Alexander Htet Kyaw, Lawson Spencer, Sasa Zivkovic, and Leslie Lok. 2023. "Gesture Recognition for Feedback Based Mixed Reality and Robotic Fabrication: A Case Study of the UnLog Tower." In *Proceedings of the 5th International Conference on Computational Design and Robotic Fabrication (CDRF 2023)*, 331-345. Shanghai: CDRF

Parke MacDowell and Diana Tomova. 2011. “Robotic Rod-bending: Digital Drawing in Physical Space.” In *Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 132-137. Banff: ACADIA

Iain Maxwell, David Pigram, and Wes McGee. 2013. “The Novel Stones of Venice: The Marching Cube Algorithm as a Strategy for Managing Mass-Customisation.” In *Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 311–318. Cambridge, Canada: ACADIA

Gwyllim Jahn, Cameron Newnham, and Matthew Beanland. 2018. “Making in Mixed Reality. Holographic Design, Fabrication, Assembly and Analysis of Woven Steel Structures.” In *Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 88–97. Mexico City: ACADIA

Huang Lee-Su and Spaw Gregory. 2023. “Augmented Reality Assisted Robotic: Tube Bending.” In *Proceedings of the 43rd Annual Conference for the Association for Computer Aided Design in Architecture (ACADIA)*, 340-349. Denver: ACADIA

Yang Song, Asterios Agkathidis, and Richard Koeck. 2022. “Augmented Masonry Design: A Design Method using Augmented Reality (AR) for Customized Bricklaying Design Algorithms.” In *10th ASCAAD Conference Proceedings*, 703-712. Debbieh: ASCAAD.

Daniela Mitterberger, Selen Ercan Jenny, Lauren Vasey, Ena Lloret-Fritschi, Petrus Aejmelaeus-Lindström, Fabio Gramazio, and Matthias Kohler. 2022. “Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-Site Robotic Plastering.” In *CHI Conference on Human Factors in Computing Systems*, 1–18. New Orleans, USA: ACM CHI.