Implementation and Evaluation of a Multi-user Digital Content Sharing Application using Mixed Reality

Shion Kimura[1], Tomoyuki Ishida[2]

[1]Graduate School of Engineering, Fukuoka Institute of Technology, Fukuoka, Japan

[2]Department of Information and Communication Engineering, Fukuoka Institute of Technology, Fukuoka, Japan

Received: October 05, 2025; Revised: November 30, 2025; Accepted: December 23, 2025; Published: December 30, 2025

Abstract

Currently, few digital content sharing systems using mixed reality (MR) adequately address the diverse needs of users, partly due to the lack of a suitable platform for content sharing. In this study, we developed a multi-user digital content sharing application leveraging MR technology. An evaluation experiment involving 30 participants was conducted, assuming use cases such as remote meetings, collaborative design, and collaborative learning. The results confirmed high operability of the content manipulation, as well as smooth performance in content generation, content manipulation, and remote user interaction. However, some participants experienced difficulty in content manipulation, indicating the need for improved operability. For practical deployment across various fields, the application must be further enhanced with domain-specific functions based on feedback obtained from the evaluation.

Keywords: Mixed Reality, Multi-User Space Sharing, Digital Content, Collaborative Work.

1 Introduction

Recent advances in digital technology have driven the rapid evolution of immersive technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR).

In VR, digital content sharing typically occurs within a fully virtualized environment. VR enables users to disconnect from the physical world and become immersed in a simulated space. Consequently, content sharing among users generally involves accessing the same virtual environment and interacting within a shared digital context. For instance, in virtual offices or classrooms, multiple users can collaboratively manipulate 3D objects and consult digital materials simultaneously [1]. However, a key limitation of VR is the lack of access to real-world contextual information, which presents ongoing challenges in achieving synchronization and integration with the physical environment.

Sharing digital content in AR offers the advantage of maintaining awareness of the physical environment, as AR overlays digital information onto the real world. A common example involves projecting 3D objects into real space using smartphones or tablets, enabling multiple users to view and interact with the same virtual object. In fields such as education and industry, AR has been applied to develop training systems integrated with real-world facilities and environments, as well as on-site operational support systems [2][3][4].

MR combines elements of both VR and AR, enabling users to interact with the real and virtual worlds simultaneously. MR systems, such as those using Microsoft HoloLens 2 [5], allow digital content placed in physical space to dynamically respond to users' movements and perspectives. This facilitates real-time collaboration, where multiple users can share the same physical space, manipulate shared digital objects, and exchange information. In the medical field, MR has been used to develop systems that enable remote experts to assist in surgeries via integrated cameras and sensors. Similarly, in manufacturing, remote engineers can provide real-time guidance to on-site workers for troubleshooting and decision-making [6][7][8]. However, existing MR-based content sharing systems remain limited in number and functionality, often failing to meet the diverse needs of users. A major contributing factor is the absence of a robust platform for digital content sharing. Moreover, many current systems only visualize the position of the user's hand, without capturing or sharing its shape, reducing the fidelity of interaction.

Therefore, this study presents the development of an MR application that enables multiple users in remote locations to intuitively share digital content in real time. By importing various types of digital content, the application provides a flexible environment for collaboration across multiple fields.

The remainder of this paper is structured as follows: Section 2 reviews related work. Section 3 outlines the objectives of the research. Section 4 details the system configuration of the proposed multi-user digital content sharing application. Section 5 describes the application itself, while Section 6 presents its evaluation. Finally, Section 7 concludes the study.

2 Related Work

Bayro et al. [9] compared the usability of head-mounted display (HMD)-based and desktop-based systems for remote collaboration, demonstrating that HMDs significantly enhance collaborative effectiveness.

Schild et al. [10] developed a multi-user VR system for medical training, specifically simulating scenarios involving anaphylactic shock.

Du et al. [11] introduced "Collaborative VR (CoVR)," a cloud-based, multi-user VR headset system designed to facilitate communication in interactive environments. Virtual CoVR has been shown to improve collaboration in construction projects.

Kaufmann et al. [12] developed "Construct3D," an AR-based 3D geometry construction tool tailored for mathematics and geometry education. It features an intuitive interface suited to a variety of instructional settings.

Gasques et al. [13] proposed "ARTEMIS," a surgical remote teaching system employing MR technology, which enables untrained medical personnel to receive real-time guidance from remote experts during emergency procedures.

Chen et al. [14] developed a human–robot teaming system using MR interfaces, demonstrating the effectiveness of MR in enhancing collaboration between humans and robots.

Sasikumar et al. [15] developed a wearable MR remote collaboration system called "Wearable RemoteFusion." The study demonstrated that sharing local eye gaze and remote hand gestures significantly enhances users' sense of co-presence.

Gong et al. [16] developed a multi-user VR system to support design review processes in manufacturing. Their findings indicate that such systems can effectively complement and improve existing engineering workflows.

3 Research Objective

This study aims to develop a multi-user digital content sharing application utilizing MR technology. The primary objective is to provide an environment in which users at remote locations can collaboratively interact with digital content overlaid on the physical world. A key feature of the application is its ease of content import, allowing for flexible use across diverse domains such as education, medicine, and manufacturing. This adaptability addresses the limitations of conventional systems that lack the versatility to meet varying user needs. The application supports real-time interaction, which is expected to enhance work efficiency and promote effective information sharing. The core functionalities of the system include

- Digital content creation and deletion: enables users to display digital content overlaid on physical space and remove it as needed.
- Voice communication: enables real-time voice conversations between users via MR HMDs, facilitating natural verbal interaction during collaboration.
- Gesture recognition: allows the MR HMD to recognize users' hand shapes and convey them to other participants. This supports intuitive, gesture-based communication and enhances non-verbal interaction.
- Content color customization: allows users to change the color of overlaid digital content. This feature supports collaborative design tasks, such as interior planning, by enabling visual modifications in real time.

By integrating these functions, the application creates an environment that supports real-time, remote collaboration through shared digital content and intuitive interaction.

4 Multi-user Digital Content Sharing Application Configuration

The configuration of the proposed system is illustrated in Figure 1. The application comprises several key components: the user, the MR collaborative work application, the MR space content server, the Photon server, and the MR shared space room.

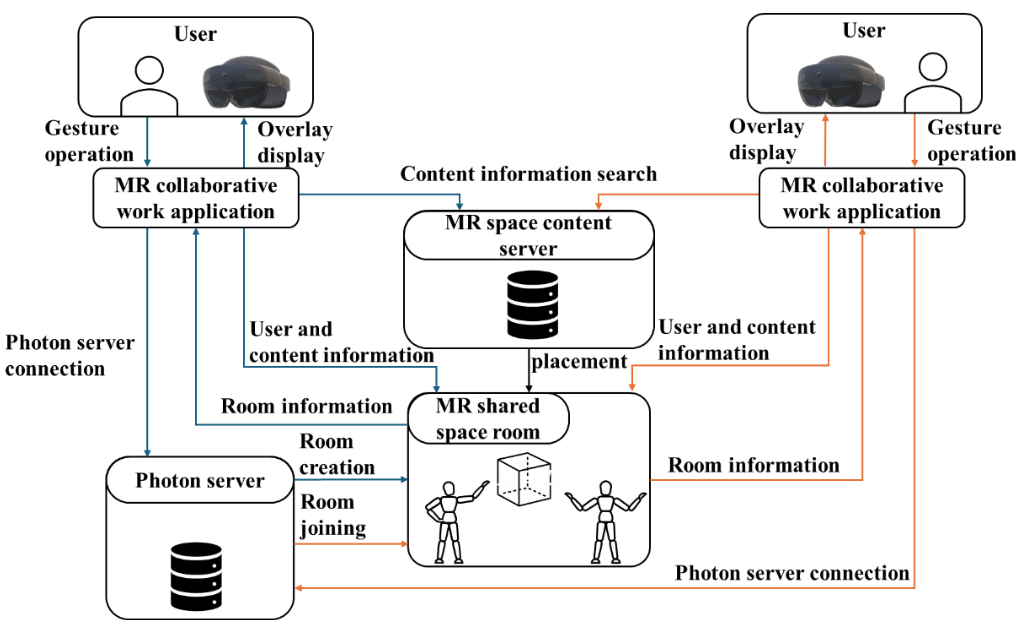

Figure 1. Multi-user digital content sharing application configuration

- User

Each user wears a HoloLens 2 device and operates within a designated MR shared space ("room"). Digital content is overlaid onto the user's physical environment, enabling interaction within the real world. All operations performed within the shared room are synchronized and visible to other users. As a result, users—regardless of physical location—experience a sense of co-presence, as if working in the same environment.

- MR collaborative work application

This application manages communication between the HoloLens 2 and the Photon server. Upon launch, it queries the Photon server to determine whether a shared room exists. If a room is available, the user joins it; otherwise, a new room is created. Once the user enters a room, their positional data, digital content coordinates, and voice data from the HoloLens 2 are transmitted to the room in real time. This information is simultaneously reflected in the applications of all other users, ensuring synchronized interaction. When a user creates new content, the application retrieves the relevant content information from the MR space content server.

- MR space content server

The MR space content server manages metadata—such as size, color, and shape—of 3D objects used within the system. Based on content requests from the application, it searches the server for the relevant data and generates the selected digital content within the shared room.

- Photon server

The Photon server [17] provides the real-time communication infrastructure that enables data synchronization across users. Each user connects to the Photon server through the application, allowing user actions and communications to be reflected instantly across all clients. The server is responsible for managing user connections, creating and maintaining rooms, and transmitting data. It synchronizes user locations and content interactions in real time, ensuring a seamless collaborative experience within the virtual shared space. Events such as content creation or manipulation are immediately propagated to all connected users to maintain consistency.

- MR shared space room

The MR shared space room is a virtual environment where multiple users collaborate in real time. Each room stores the shared digital content and interaction data, which are synchronized across all users. As users manipulate digital content, their positional data and state changes are transmitted instantly to other participants, creating a sense of co-presence and shared interaction. By joining a room, users can view and interact with overlaid digital content from a common spatial perspective, enabling natural communication and collaborative work.

5 Multi-user Digital Content Sharing Application

The developed application enables users in remote locations to share and collaboratively manipulate digital content in real time. This section outlines the key implementation aspects and core functions of the system. The application was developed using Microsoft's MR Toolkit (MRTK) [18], a development framework that facilitates efficient MR application creation within Unity. The Unity project was deployed to HoloLens 2 using Visual Studio 2022. To enable real-time content sharing among multiple users, the application utilizes Remote Procedure Calls (RPCs) provided by Photon Unity Networking 2 (PUN2) [19]. PUN2 is designed to simplify the development of multiplayer applications, offering features such as real-time communication, data synchronization, matchmaking, and event handling through Photon's cloud services. In particular, the RPC mechanism allows methods to be executed across networked clients. This enables a user's actions to be immediately reflected on other clients' devices, ensuring consistent interaction and efficient propagation of events. The RPC execution process is illustrated in Figure 2.

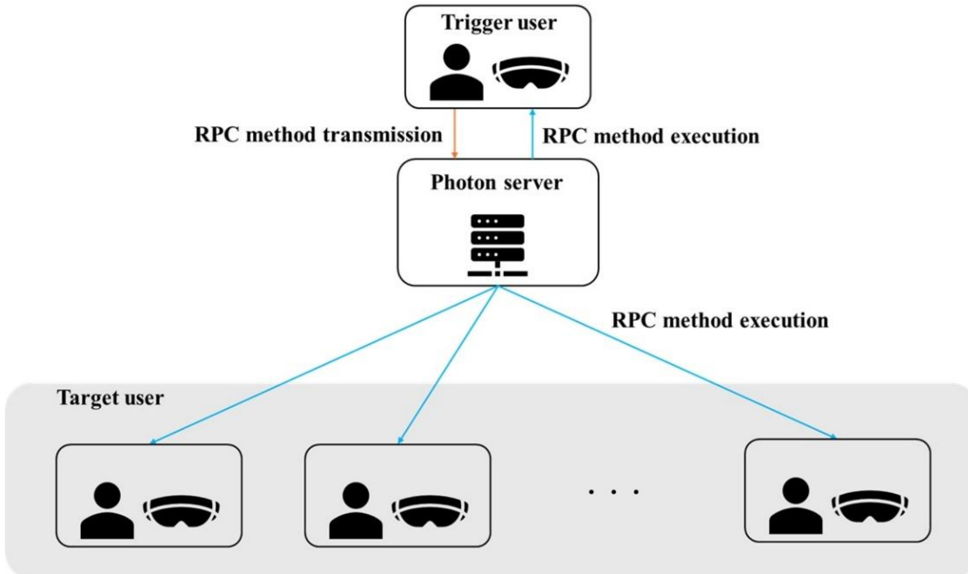

Figure 2. RPC execution procedure

To enable real-time voice communication, the application integrates Photon Voice 2 [20], a Unity-compatible toolkit that facilitates low-latency voice transmission using the built-in microphone and speaker of the HoloLens 2. The implementation relies on four primary components:

- Recorder: captures audio input from the HoloLens 2 microphone and transmits it to other users in the session.
- Speaker: outputs incoming voice data to the local scene, enabling users to hear remote participants.
- Photon Voice View: automatically configures the speaker component to play voice data received from remote users on the local device.
- Pun Voice Client: manages the connection to the Photon server required for establishing and maintaining voice communication.

The processing flow of these four components is illustrated in Figure 3. First, the Pun Voice Client establishes a connection with the Photon server. Once connected, the Photon Voice View component automatically configures the Recorder and Speaker components to enable voice communication. After setup, users can engage in real-time conversation. For instance, audio captured by User A's Recorder is transmitted through the Photon server and played by User B's Speaker component.

The user interface of the application incorporates a hand menu, implemented using a prefab provided by MRTK. This menu appears when the user gazes at their hand while wearing the HoloLens 2 and automatically hides when the hand is removed from the field of view. This dynamic visibility ensures that the interface is accessible only when needed, preserving a wide field of view during operation. The hand menu is fully customizable, allowing developers to configure its contents as required. Consequently, new functions can be easily integrated into the application by modifying the hand menu prefab, enabling seamless extension of functionality. Several functions are mapped to buttons on the hand menu, which can be activated through simple selection. As shown in Figure 4, the menu includes options such as Create, Delete, and Color Panel, corresponding to the content generation function, content deletion function, and color customization panel, respectively. The gesture recognition process is illustrated in Figure 5. When the system detects hand joints, it places a cube at each joint to visualize hand movement. These cubes are synchronized across all users via the Photon View component, enabling real-time sharing of gesture information in the collaborative environment.

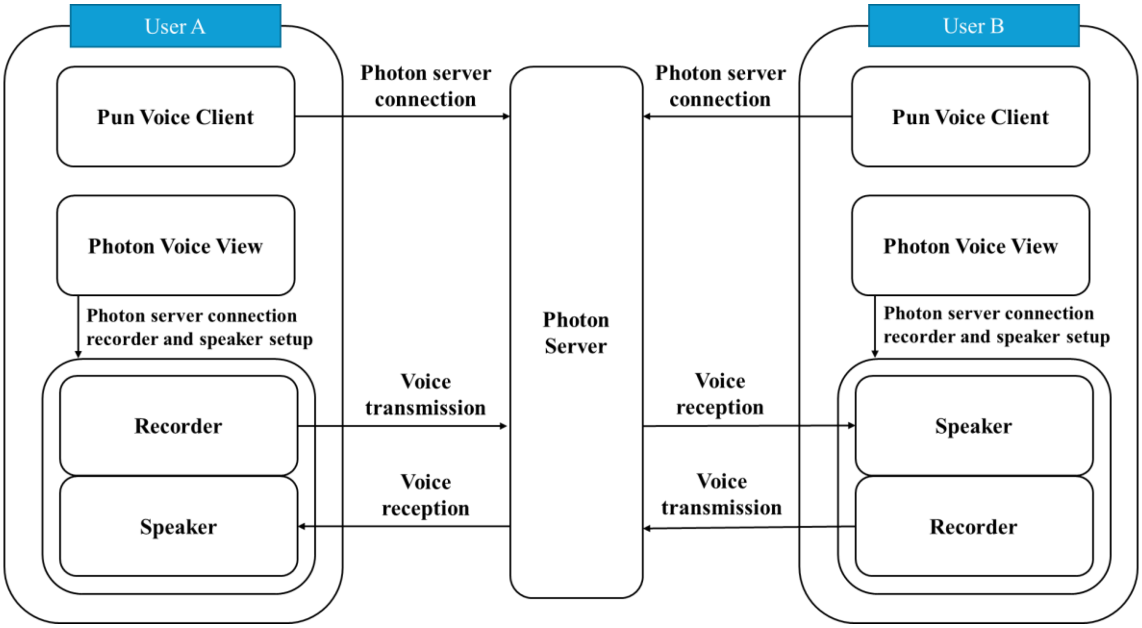

Figure 3. RPC execution process flow

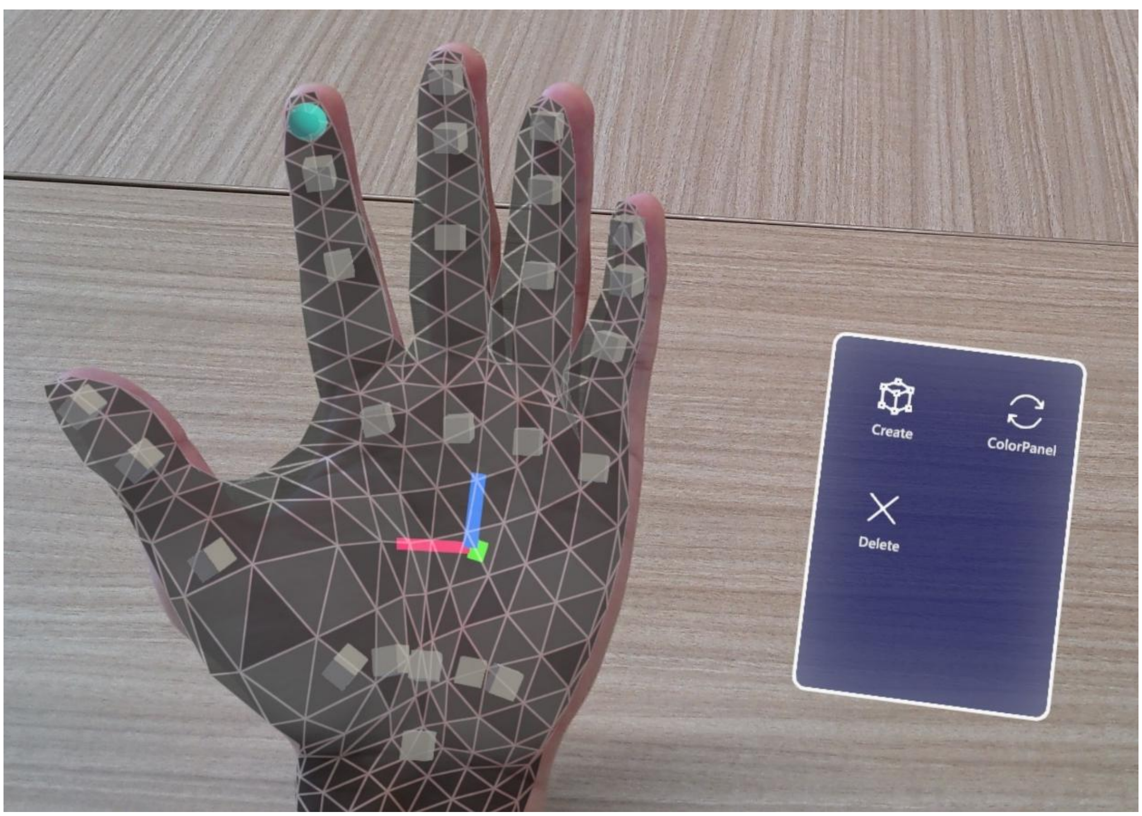

Figure 4. Hand menu

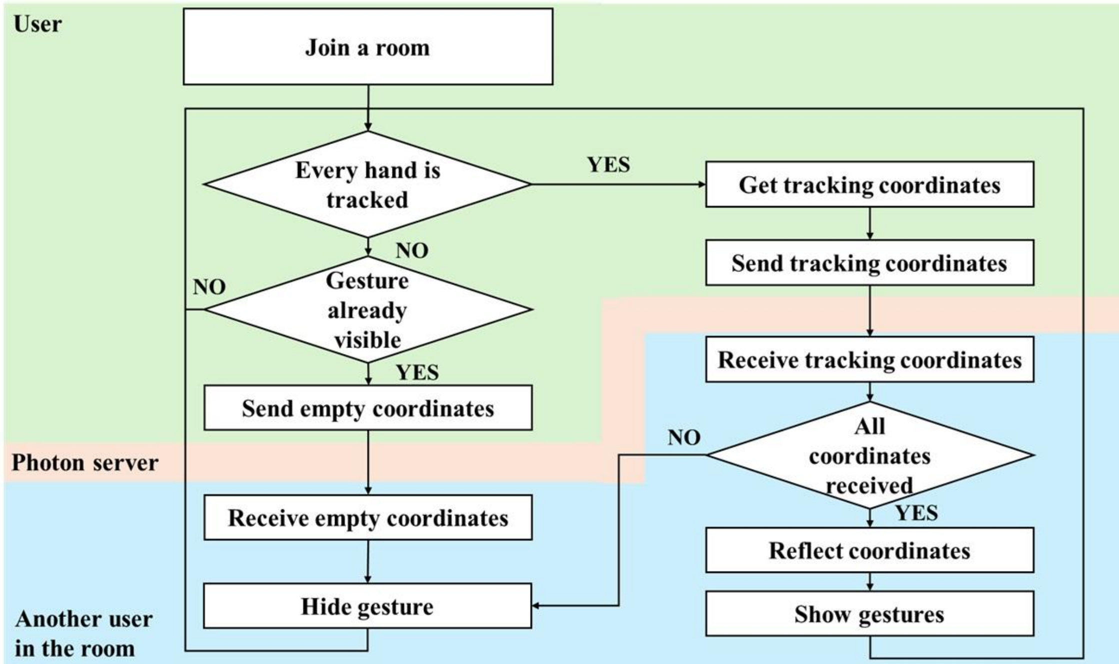

Figure 5. Process flow of the gesture function

The content generation function allows users to create digital content within a shared room. When the Create button on the hand menu (Figure 4) is selected, a panel appears in front of the user, as shown in Figure 6. This panel displays a list of buttons, each labeled with the name of a content item that can be placed in the MR environment.

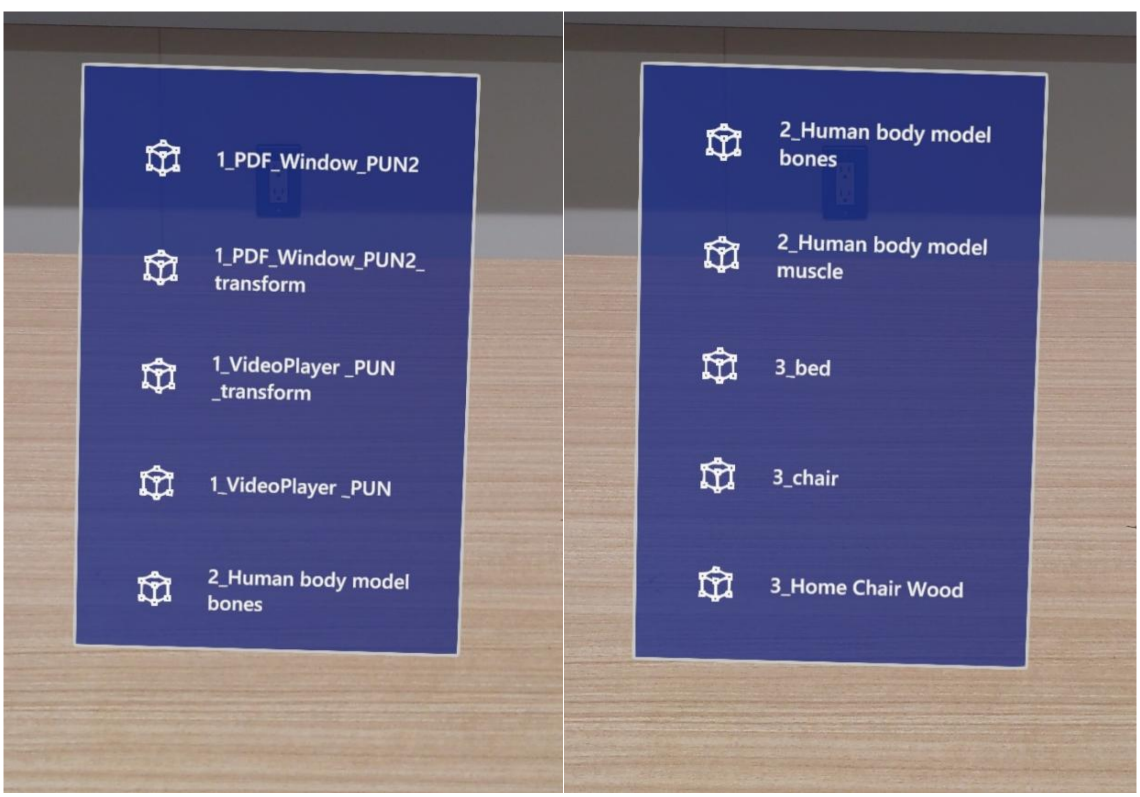

Figure 6. Object generation selection panel

When a button on the panel is pressed, the corresponding digital content is generated in front of the user, as shown in Figure 7. To enable this, all content must first be imported into Unity's Resources folder. For proper synchronization across users, the components listed in Table 1 must also be attached to each content item. The panel shown in Figure 6 is a customized version of MRTK's Scrolling Object Collection. This implementation allows users to scroll through the button list, enabling a compact display of numerous content items. As a result, the interface remains scalable and responsive, even as the number of available content items increases.

Figure 7. Generated content

Table 1. List of components to attach to the content

Component name	Component role
Box Collider	Adds collision detection to the content
Photon View	Enables communication via the Photon server
Generic Net Sync	Synchronizes content coordinates across users via the Photon server
Ownership Handler	Manages ownership of content to prevent simultaneous manipulation by multiple users
Object Manipulator	Enables content manipulation
Constraint Manager	Applies constraints on content manipulation (e.g., limits the range of user manipulation)
Send Object Manager	Track objects that the user has grabbed
Bounding Box Outline	Generates an outline around content tracked by the Send Object Manager
Line renderer	Configures the thickness, color, other visual properties of the bounding box outline

This study also implements a content deletion function for removing digital objects placed within a room. To delete content, the user must first grab the target object and then select the Delete button, as illustrated in Figure 8–11. During this process, a visual guide—displayed as a line (Figure 9)—helps the user confirm the selected content. Upon selection of the content and activation of the Delete button (Figure 10), a deletion confirmation screen appears (Figure 11). This confirmation step is designed to prevent accidental deletions and ensure that users intentionally remove only the desired content.

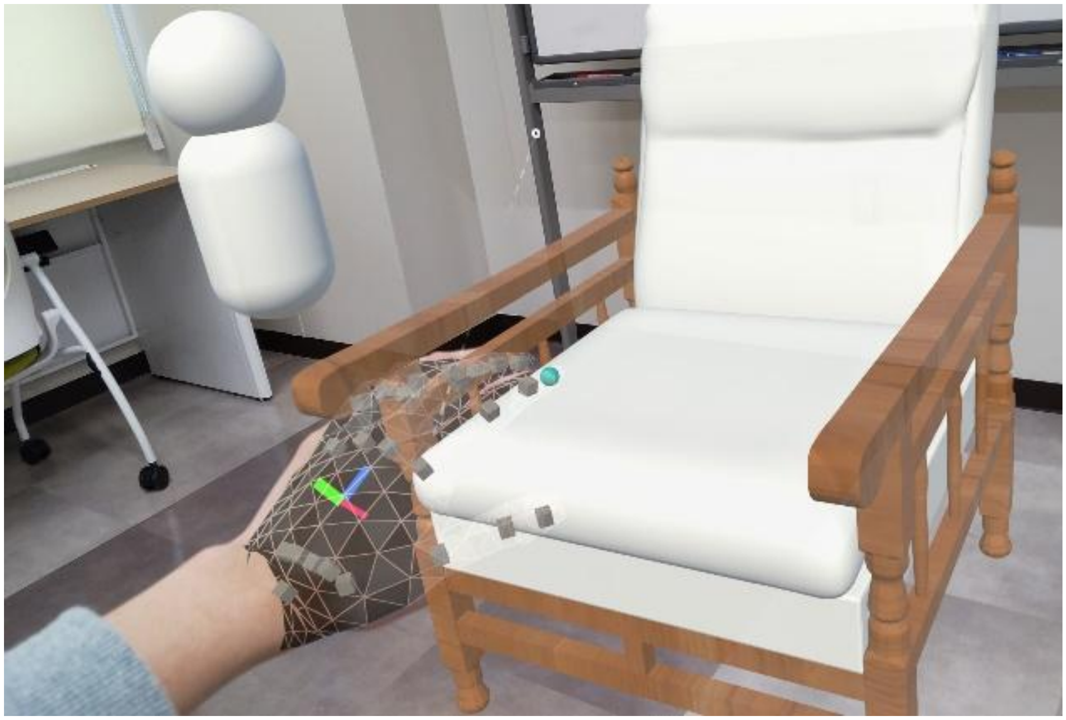

Figure 8. Grabbing the content to be deleted

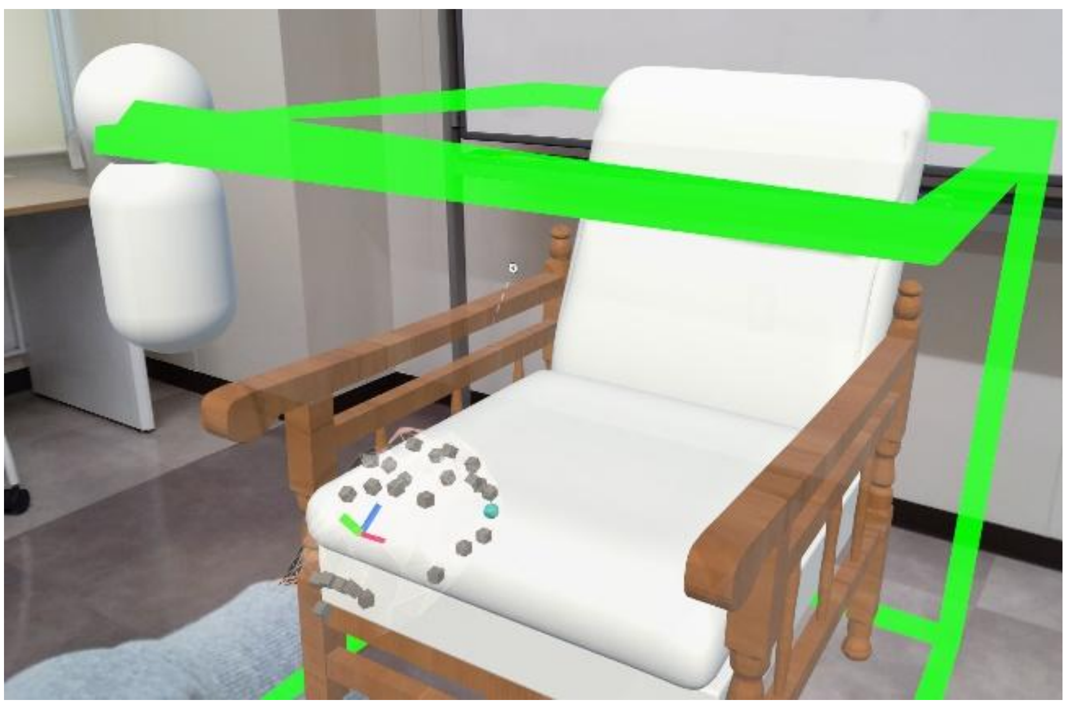

Figure 9. Selected content

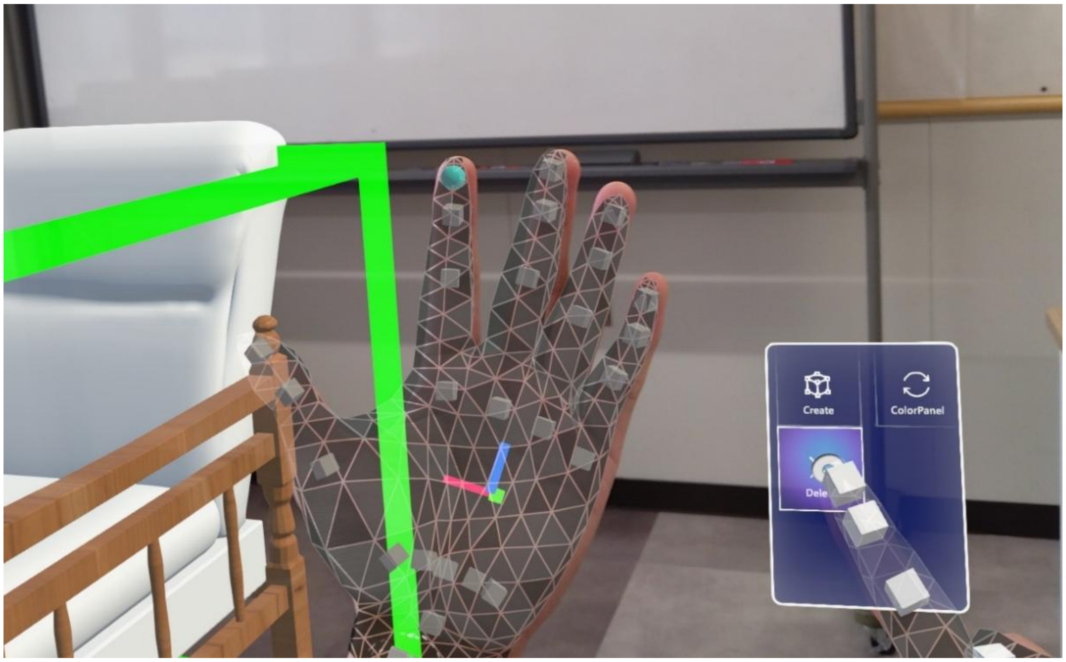

Figure 10. Menu screen for content deletion

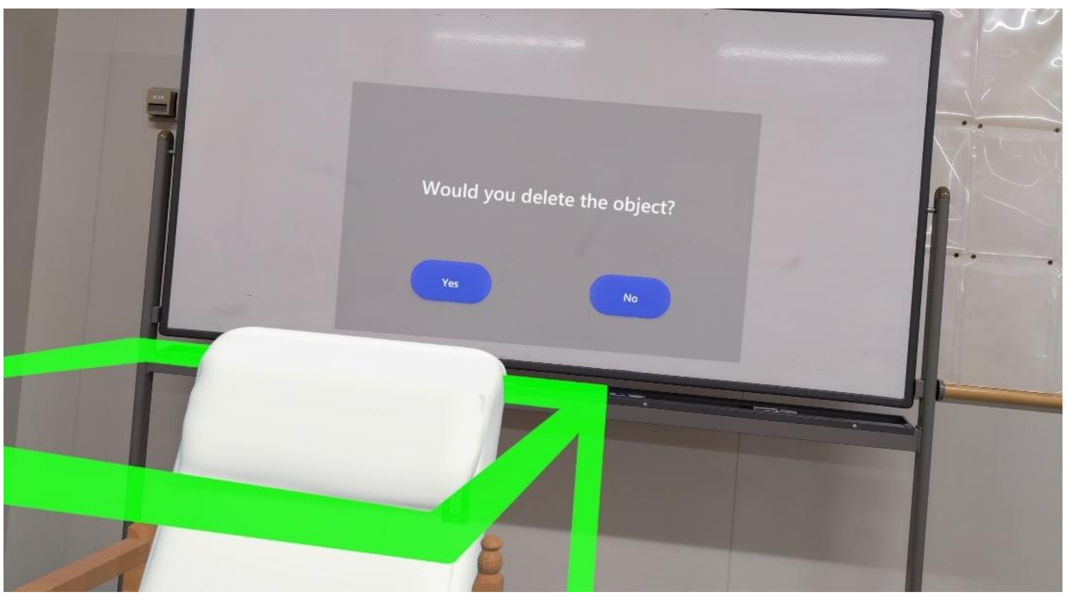

Figure 11. Deletion confirmation screen

This section describes the color panel used to change the color of digital content. The panel is a customized version of the MRTK-provided color picker, adapted to support multi-user interaction. The color panel comprises four sub-panels, each offering a different method for adjusting color parameters. On the left side of each sub-panel, four vertically aligned buttons serve as panel selection controls, allowing users to switch between different color adjustment modes. To ensure consistency, material updates made using the four color panels are synchronized across users by transmitting red, green, blue, and alpha (RGBA) values through RPC methods.

When a user selects the Color Panel button from the hand menu (Figure 4), the system retrieves the View ID, a unique identifier assigned to the currently grabbed content. This View ID is passed as an argument to an RPC method, which triggers the display of the color panel across all users. The processing flow of this RPC method is illustrated in Figure 12. Using the View ID, the system identifies the relevant content and searches for associated game objects named Target Object (Mesh) and Anchor. The Target Object (Mesh) represents the component whose material color will be modified. The Anchor object provides reference coordinates, determining the display position of the color panel relative to the parent object when it is selected. Because the color panel uses the View ID to target specific content, different instances of the same content type can be independently colored (Figure 13). Moreover, since only color parameters are synchronized, each user can freely position and interact with their own instance of the color panel. Figure 14 presents the local user's perspective, which includes the avatar of a remote collaborator. Figure 15 shows the corresponding perspective of the remote user featured in Figure 14.

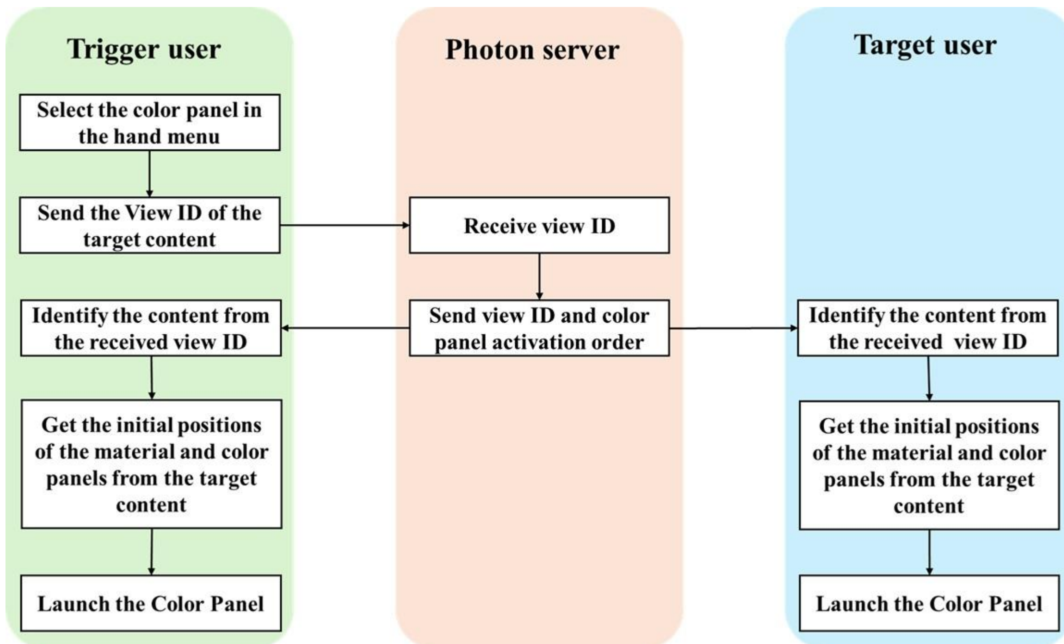

Figure 12. Process flow after color panel launch

Figure 13. Changing the same content to different colors

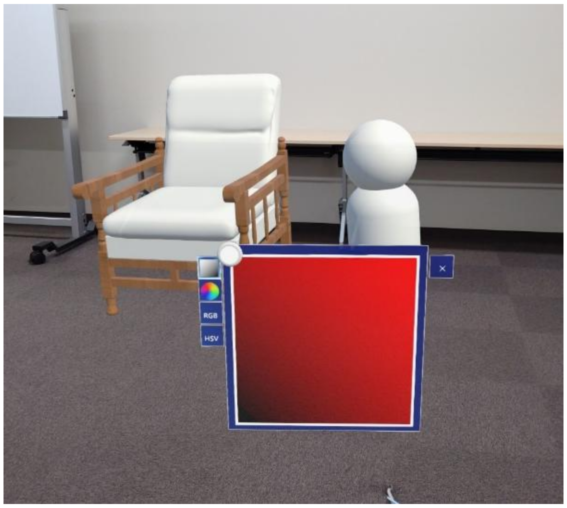

Figure 14. Local user's viewpoint

Figure 15. Remote user's viewpoint

An example use case of the proposed system is in remote meetings, where users are expected to share materials such as PowerPoint presentations, documents, and videos. An illustration of this content sharing scenario is shown in Figure 16.

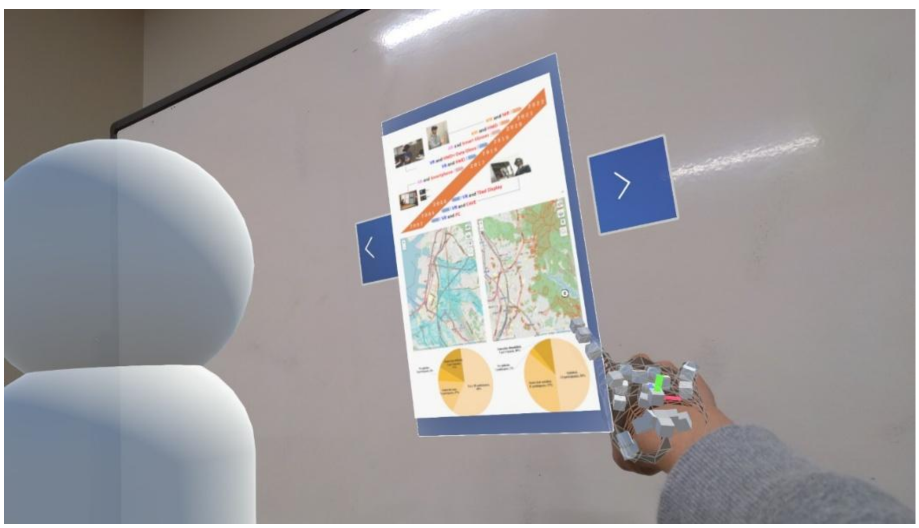

Figure 16. Sharing of meeting materials

6 Multi-user Digital Content Sharing Application Evaluation

An evaluation experiment was conducted with 30 participants, primarily university students, to assess the usability and effectiveness of the proposed application. Participants first used the application and then completed an evaluation questionnaire based on their experience.

Participant age distribution is presented in Figure 17, while Figure 18 shows the breakdown of prior experience with HMDs. The majority of participants were in their 20s. Of the 30 participants, 17 had no prior experience using HMDs, whereas 13 had some level of experience.

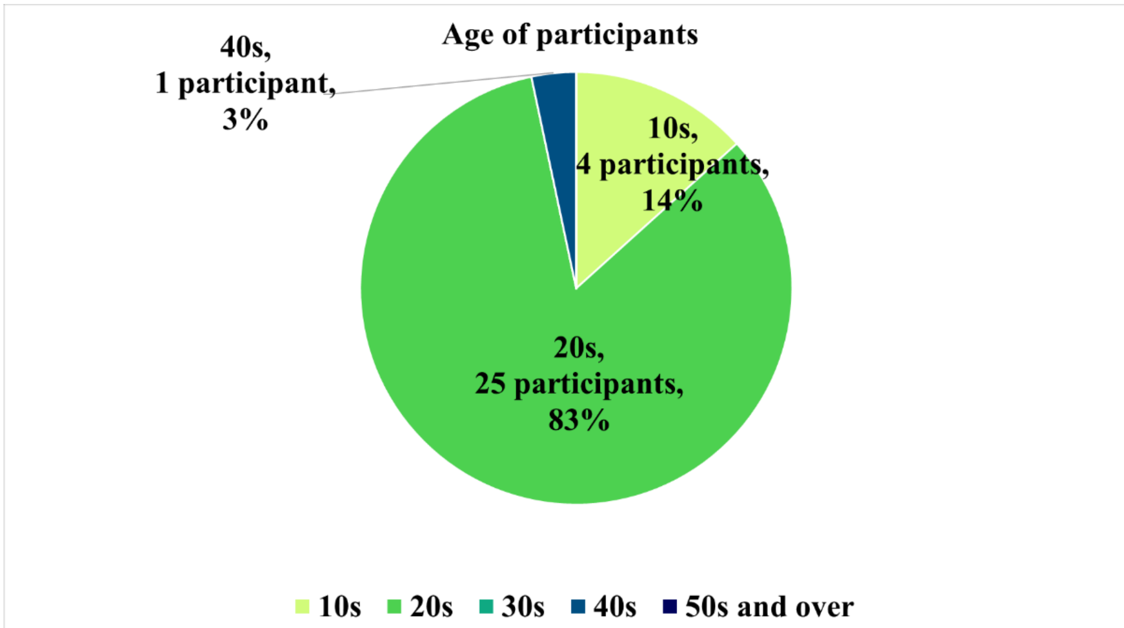

Figure 17. Age of participants (n = 30)

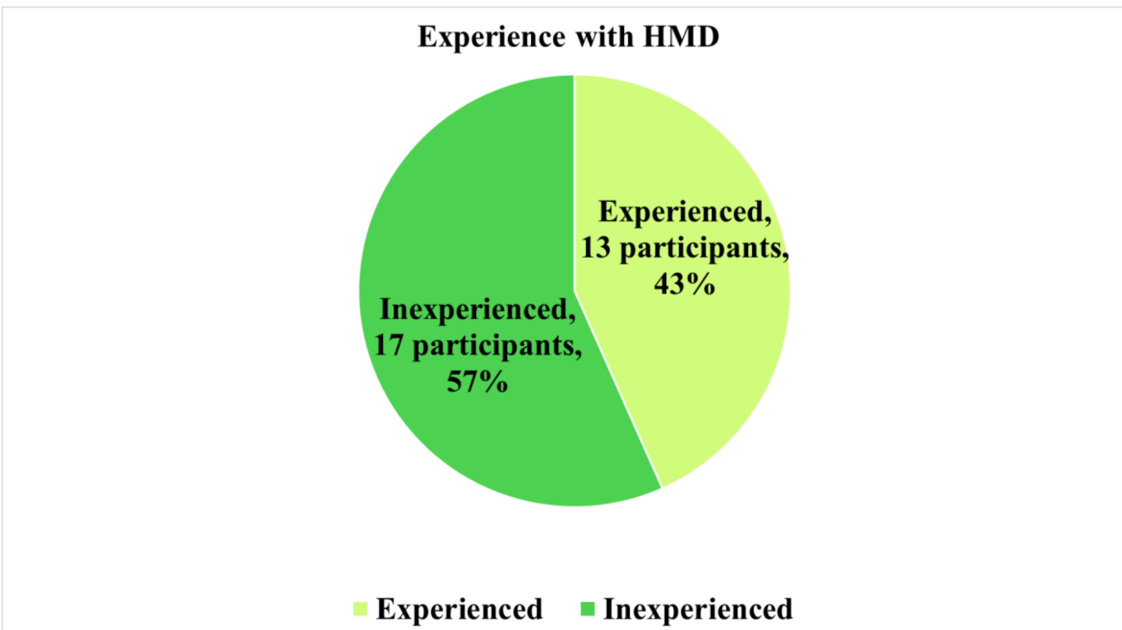

Figure 18. Experience with HMD (n = 30)

The evaluation results related to the operability of content manipulation are shown in Figure 19. Here, content manipulation refers to the ability to grab and move user-generated content. Overall, 76% of participants responded with “easy” or “somewhat easy,” indicating that the content manipulation function was generally user-friendly. Conversely, 24% of participants responded with “no opinion” or “somewhat difficult.” A breakdown by HMD experience is shown in Figure 20 (HMD-inexperienced participants) and Figure 21 (HMD-experienced participants). Among those without prior HMD experience, 36% answered “no opinion” or “somewhat difficult,” suggesting that challenges in perceiving depth and spatial distance may have impacted usability. In contrast, 92% of experienced HMD users found the manipulation “easy” or “somewhat easy,” confirming that the system is intuitive for those with prior exposure to MR interfaces. Participants who rated the experience as “somewhat difficult” provided comments such as “it was difficult to grasp the content” and "it was difficult to rotate the content," highlighting specific interaction challenges.

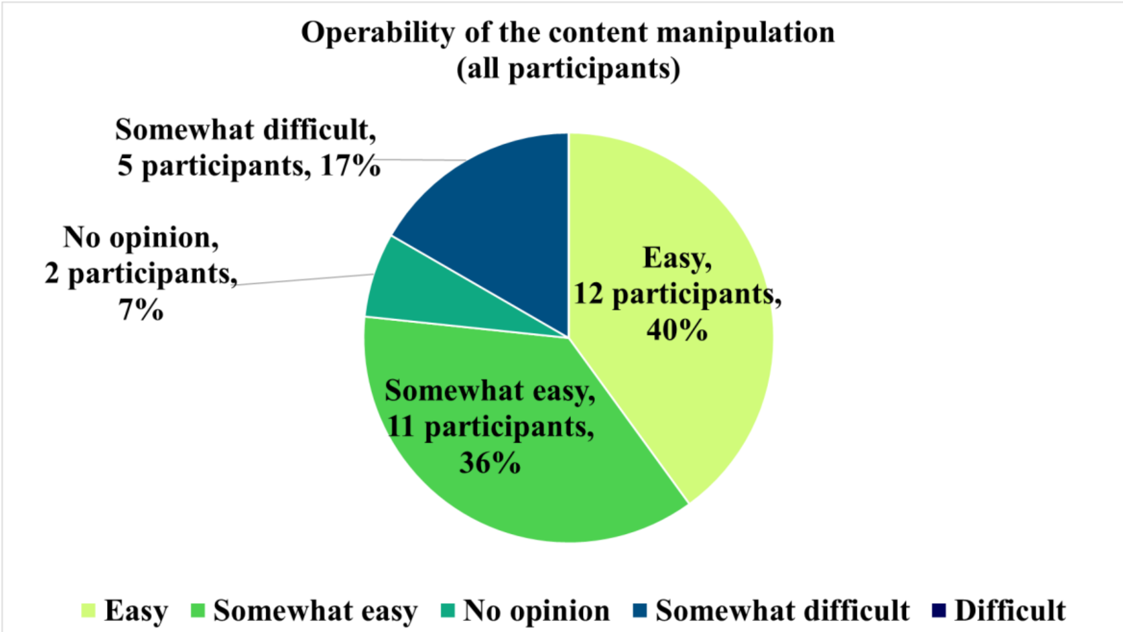

Figure 19. Operability of the content manipulation ($n = 30$)

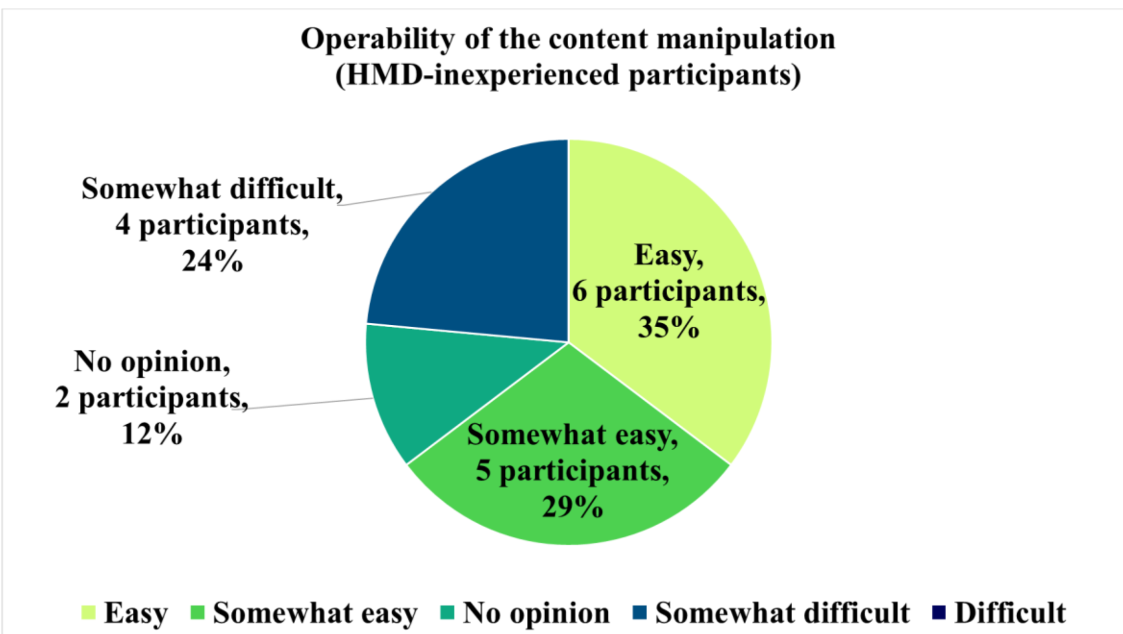

Figure 20. Operability of the content manipulation for the HMD-inexperienced participants ($n = 17$)

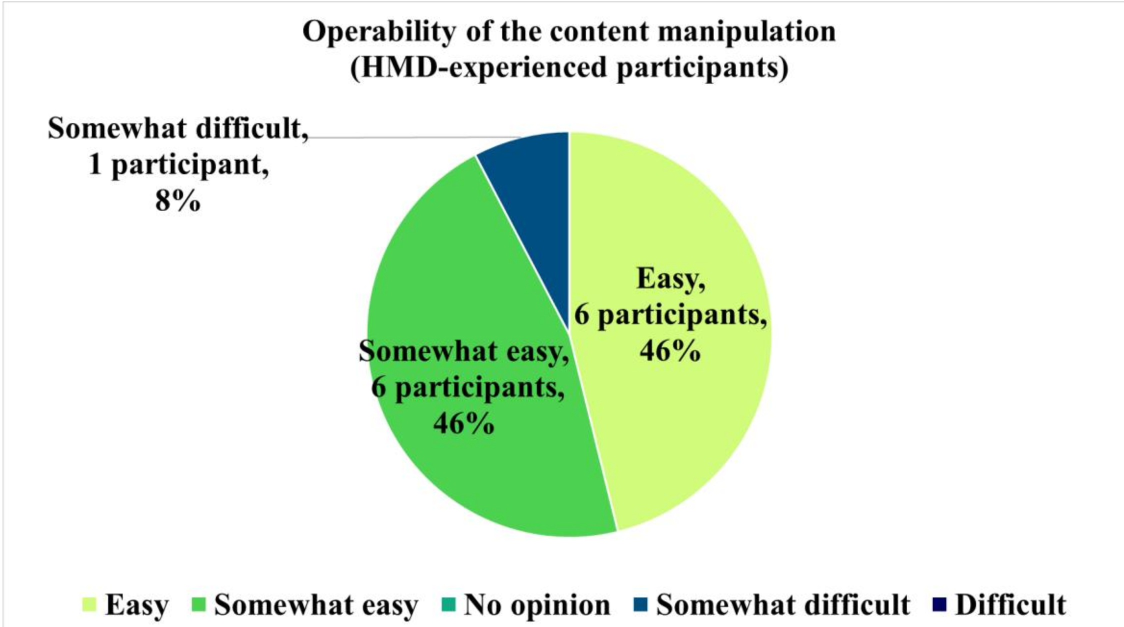

Figure 21. Operability of the content manipulation for the HMD-experienced participants (n = 13)

The evaluation results regarding user satisfaction with the conversation function are presented in Figure 22. A total of 90% of participants responded with “satisfied” or “somewhat satisfied,” indicating that the conversation function of the application was well received by most users. However, some participants noted that “the voice sounds a little delayed,” which likely contributed to responses of “no opinion” or “somewhat dissatisfied.”

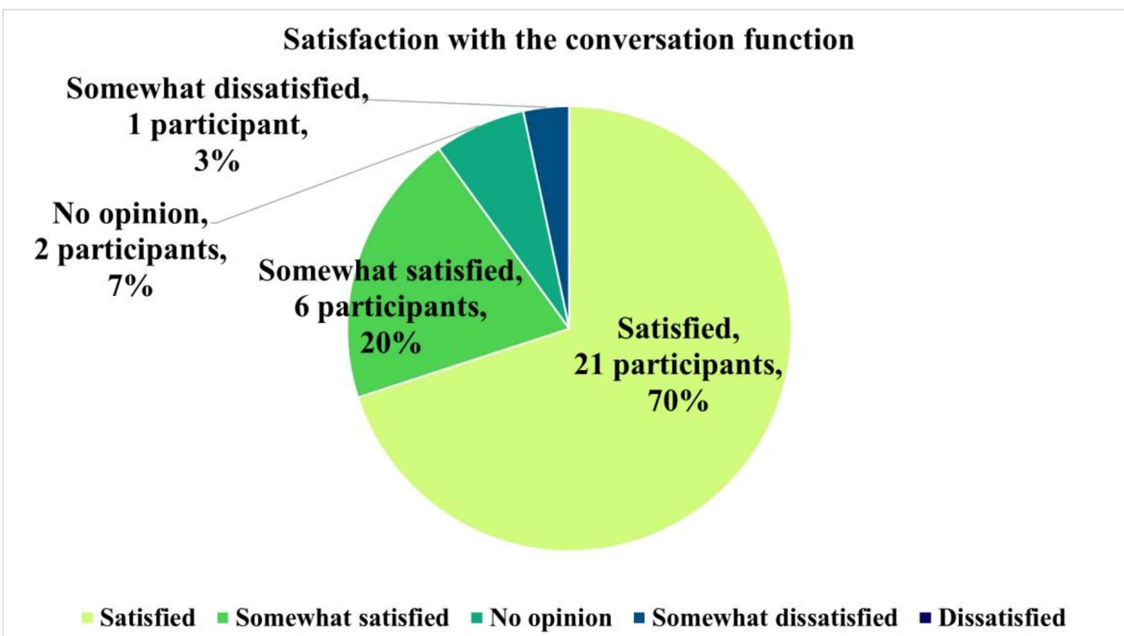

Figure 22. Satisfaction with the conversation function (n = 30)

The evaluation results related to the effectiveness of sharing content between remote users are shown in Figure 23. All participants responded with “effective” or “somewhat effective,” confirming that the application was highly effective in supporting content sharing among geographically separated users.

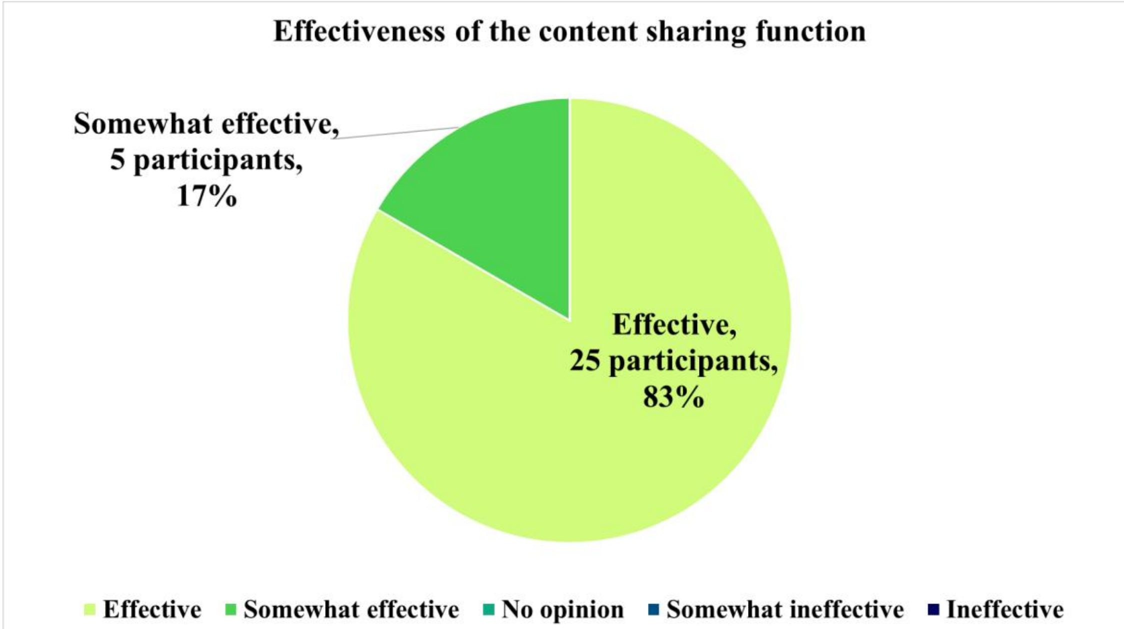

Figure 23. Effectiveness of the content sharing function (n = 30)

The evaluation results regarding the effectiveness of the gesture function are shown in Figure 24. A total of 94% of participants responded with "effective" or "somewhat effective," indicating a high level of perceived effectiveness. However, 6% of participants selected "no opinion," which may be attributed to limitations in recognizing complex gestures.

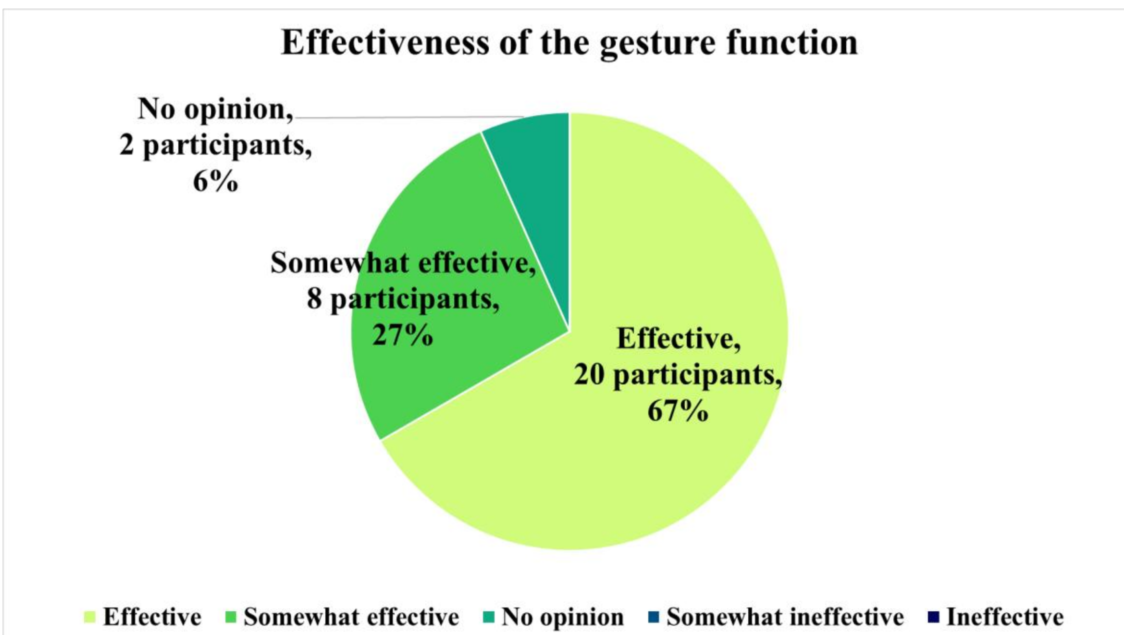

Figure 24. Effectiveness of the gesture function (n = 30)

The evaluation results regarding the applicability of the application to other fields are presented in Figure 25. Overall, 93% of participants responded with "possible" or "somewhat possible," while 7% responded with "no opinion." These results suggest that the application holds strong potential for use in other domains. Participant feedback indicated potential applications in fields such as education, architecture, medicine (including surgery and nursing care), and entertainment.

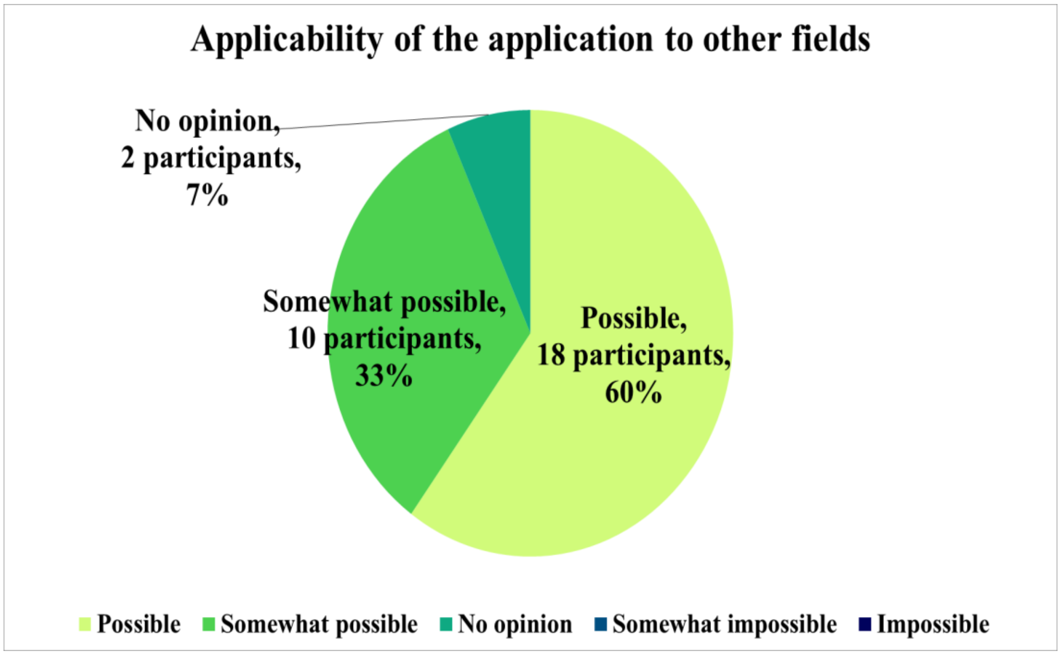

Figure 25. Applicability of the application to other fields (n = 30)

The time lag between pressing the button to generate content and the actual appearance of the content was evaluated. As shown in Figure 26, all participants responded that the content was "smoothly generated," indicating that no noticeable time lag was observed between the button press and content generation.

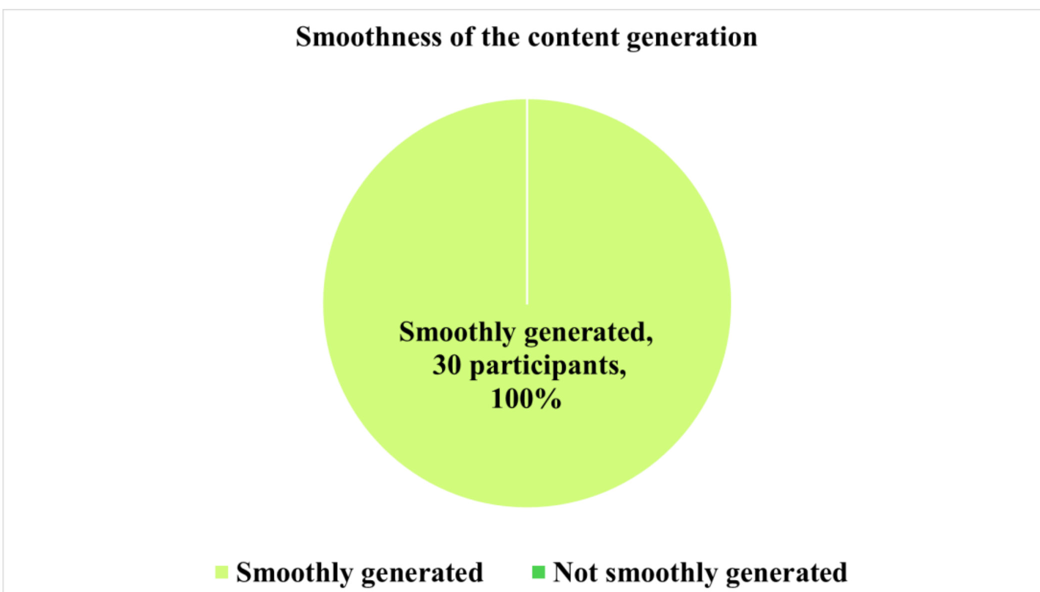

Figure 26. Smoothness of the content generation (n = 30)

The smoothness of content manipulation was also evaluated, specifically the manipulation of grabbing and moving content. The evaluation results, shown in Figure 27, indicate that 97% of participants found the manipulation to be "smooth." This confirms that most users were able to manipulate content without difficulty. One participant who responded "not smoothly manipulated" commented that "content manipulation was difficult," likely due to challenges in grabbing the content. However, many participants also noted that this did not interfere with their overall experience. Therefore, it is expected that operability will improve as users become more familiar with the system.

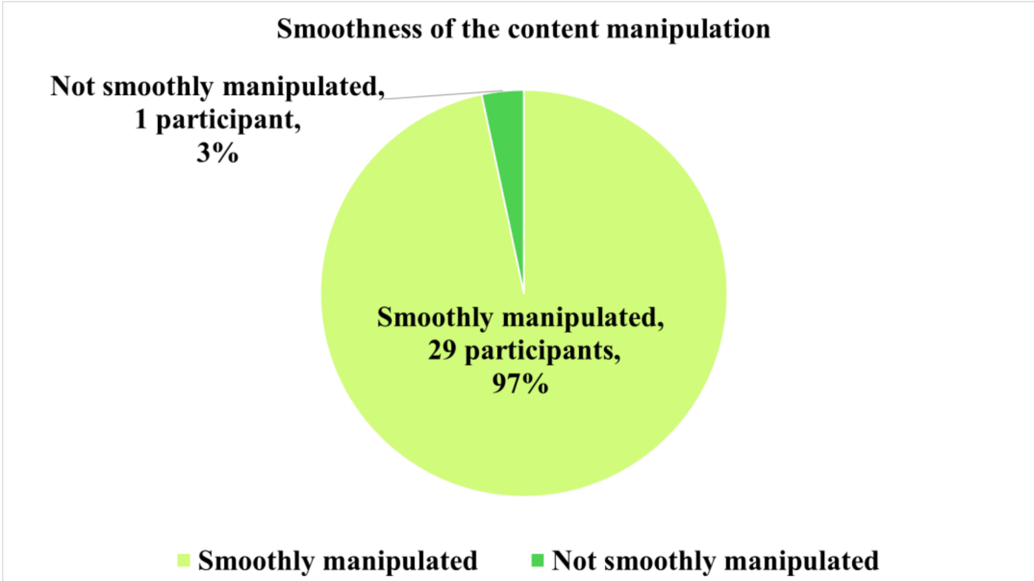

Figure 27. Smoothness of the content manipulation (n = 30)

Whether the movements and color changes of other users displayed on the HMD were reflected smoothly was assessed. The evaluation results, shown in Figure 28, indicate that all participants responded with "smoothly reflected," confirming that the application enables seamless collaboration among multiple users.

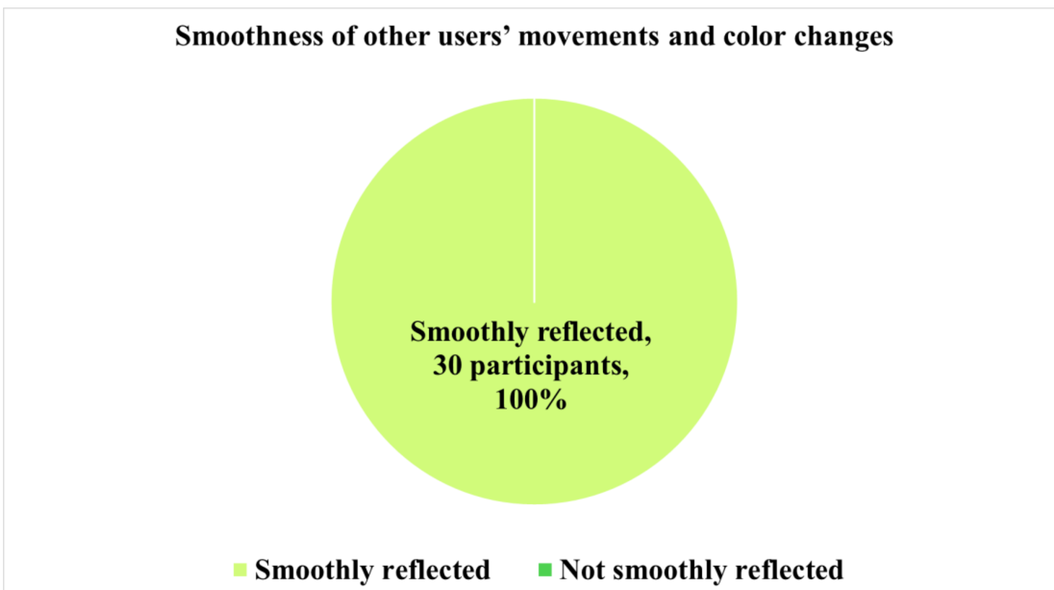

Figure 28. Smoothness of other users' movements and color changes (n = 30)

7 Conclusion and Future Work

In this study, we developed a digital content sharing application using MR technology. The goal of this application is to provide an environment in which multiple users at remote locations can collaboratively interact with digital content overlaid on the real world. A key feature of the application is its ease of importing digital content, making it adaptable for a wide range of fields such as education, medicine, and manufacturing. For example, in meetings, sharing images and videos can create the sensation of being in the same physical space.

In the medical field, sharing digital models of the human body enables remote collaborative learning and surgical simulation. Similarly, in the design field, users in different locations can collaboratively select furniture designs in real time by adjusting colors. This level of flexibility empowers users to apply the system in ways tailored to their specific domains, addressing the limitations of conventional systems that struggle to accommodate diverse needs.

To evaluate the multi-user digital content sharing application, an experiment was conducted with 30 participants. The results confirmed high operability of the content manipulation. In addition, the application received favorable evaluations for the smoothness of content generation, content manipulation, remote user movement, and color changes. However, it was also found that some participants experienced difficulty manipulating the digital content, indicating room for improvement in operability. One identified cause of this issue is the difficulty in perceiving the distance between the user and the content. To address this, it may be necessary to adjust the content's collision detection. Moreover, providing instructional materials—such as an explanatory video on how to interact with the content prior to use—could help users become more comfortable with depth perception and improve the overall user experience.

In this study, we briefly introduced example use cases of the prototype application in fields such as remote conferencing, medicine, and design. These examples serve as initial demonstrations, and in the future, it will be necessary to implement functions tailored to the specific requirements of each field. Furthermore, based on feedback from the evaluation experiment, we are considering extending the application to additional domains, including architecture and education.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number JP23K11666. This paper is an extended version of the work [21] originally presented at the 19th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS-2025), Fukuoka, Japan, July 2-4, 2025.

References

[1] Monahan, T., McArdle, G., Bertolotto, M. (2008). Virtual reality for collaborative e-learning. Computers & Education, 50(4) 1339-1353. https://doi.org/10.1016/j.compedu.2006.12.008

[2] Marques, B., Silva, S., Alves, J., Rocha, A., Dias, P., Santos, B. S. (2022). Remote collaboration in maintenance contexts using augmented reality: insights from a participatory process. International Journal on Interactive Design and Manufacturing (IJIDeM), 16, 419-438. https://doi.org/10.1007/s12008-021-00798-6

[3] Liarokapis, F., Mourkoussis, N., White, M., Darcy, J., Sifniotis, M., Petridis, P., Basu, A., Lister, P. F.. (2004). Web3D and augmented reality to support engineering education. World Transactions on Engineering and Technology Education, 3(1), 11-14.

[4] Regenbrecht, H., Baratoff, G., Wilke, W. (2005). Augmented reality projects in the automotive and aerospace industries. IEEE Computer Graphics and Applications, 25(6), 48-56. https://doi.org/10.1109/MCG.2005.124

[5] Microsoft. Microsoft HoloLens | Mixed Reality Technology for Business. https://www.microsoft.com/en-us/hololens, [Online; Accessed in December 2025].

[6] Simone, M., Galati, R., Barile, G., Grasso, E., De Luca, R., Cartanese, C., Lomonaco, R., Ruggieri, E., Albano, A., Rucci, A., Grassi, G. (2021). Remote mentoring in laparotomic and laparoscopic cancer surgery during Covid-19 pandemic: an experimental setup based on mixed reality. Medical Education Online, 26(1), https://doi.org/10.1080/10872981.2021.1996923

[7] Roth, D., Yu, K., Pankratz, F., Gorbachev, G., Keller, A., Lazarovici, M., Wilhelm, D., Weidert, S., Navab, N., Eck, U. (2021). Real-time Mixed Reality Teleconsultation for Intensive Care Units in Pandemic Situations. In Proc. of the 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (693-694), Lisbon, Portugal, May, 2021. https://doi.org/10.1109/VRW52623.2021.00229

[8] Li, Y., Zhang, Z., Li, X., Guan, S. (2021). Research on Equipment Maintenance Guidance Technology Based on MR and Digital Twin. In Proc. of the 2021 5th International Conference on Electronic Information Technology and Computer Engineering (244-248), Xiamen, China, October, 2021. https://doi.org/10.1145/3501409.3501454

[9] Bayro, A., Ghasemi, Y., Jeong, H. (2022). Subjective and Objective Analyses of Collaboration and Co-

Presence in a Virtual Reality Remote Environment. In Proc. of the 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (485-487), Christchurch, New Zealand, March, 2022. https://doi.org/10.1109/VRW55335.2022.00108

[10] Schild, J., Misztal, S., Roth, B., Flock, L., Luiz, T., Lerner, D., Herkersdorf, M., Weaner, K., Neuberaer, M., Franke, A., Kemp, C., Pranqhofer, J., Seele, S., Buhler, H., Herpers, R. (2018). Applying Multi-User Virtual Reality to Collaborative Medical Training. In Proc. of the 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (775-776), Tuebingen/Reutlingen, Germany, March, 2018. https://doi.org/10.1109/VR.2018.8446160

[11] Du, J., Shi, Y., Zou, Z., Zhao, D. (2018). CoVR: Cloud-Based Multiuser Virtual Reality Headset System for Project Communication of Remote Users. Journal of Construction Engineering and Management, 144(2), 04017109. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001426

[12] Kaufmann, H., Schmalstieg, D. (2003). Mathematics and geometry education with collaborative augmented reality. Computers & Graphics, 27(3), 339-345. https://doi.org/10.1016/S0097-8493(03)00028-1.

[13] Gasques, D., Johnson, J. G., Sharkey, T., Feng, Y., Wang, R., Xu, Z. R., Zavala, E., Zhang, Y., Xie, W., Zhang, X., Davis, K., Yip, M., Weibel, N. (2021). ARTEMIS: A Collaborative Mixed-Reality System for Immersive Surgical Telementoring. In Proc. of the 2021 CHI Conference on Human Factors in Computing Systems (1-14), Yokohama, Japan, May, 2021. https://doi.org/10.1145/3411764.3445576

[14] Chen, J., Sun, B., Pollefeys, M., Blum, H. (2024). A 3D Mixed Reality Interface for Human-Robot Teaming. In Proc. of the 2024 IEEE International Conference on Robotics and Automation (11327-11333), Yokohama, Japan, May, 2024. https://doi.org/10.1109/ICRA57147.2024.10611017

[15] Sasikumar, P., Gao, L., Bai, H., Billinghurst, M. (2019). Wearable RemoteFusion: A Mixed Reality Remote Collaboration System with Local Eye Gaze and Remote Hand Gesture Sharing. In Proc. of the 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (393-394), Beijing, China, October, 2019. https://doi.org/10.1109/ISMAR-Adjunct.2019.000-3

[16] Gong, L., Söderlund, H., Bogojevic, L., Chen, X., Berce, A., Fast-Berglund, A., Johansson, B. (2020). Interaction design for multi-user virtual reality systems: An automotive case study. Procedia CIRP, 93, 1259-1264. https://doi.org/10.1016/j.procir.2020.04.036

[17] Photon. Server 5 Photon Server Intro | Photon Engine. https://doc.photonengine.com/server/current/getting-started/photon-server-intro/, [Online; Accessed in December 2025].

[18] Microsoft. MRTK2-Unity Developer Documentation - MRTK 2 | Microsoft Learn. https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05, [Online; Accessed in December 2025].

[19] Photon. Pun 2 Introduction | Photon Engine. https://doc.photonengine.com/pun/current/getting-started/pun-intro, [Online; Accessed in December 2025].

[20] Photon. Voice 2 Voice Intro | Photon Engine. https://doc.photonengine.com/voice/current/getting-started/voice-intro, [Online; Accessed in December 2025].

[21] Kimura, S., Ishida, T. (2025). Multimedia Content Collaborative Work Support System, Proc. of the 19th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (1-9), Fukuoka, Japan, July, 2025. https://doi.org/10.1007/978-3-031-96093-2_1