# Extended Reality Collaboration: Virtual and mixed reality system for collaborative design and holographic-assisted on-site fabrication

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**Abstract.** Most augmented and virtual applications in architecture, engineering, and construction focus on structured and predictable manual activities and routine cases of information exchange such as quality assurance or design review systems. However, collaborative design activities or tasks such as complex negotiation, task specification, and interaction are not yet sufficiently explored. This paper presents a mixed-reality immersive collaboration system that enables bi-directional communication and data exchange between on-site and off-site users, mutually accessing a digital twin. Extended Reality Collaboration (ERC) allows building site information to inform design decisions and new design iterations to be momentarily visualized and evaluated on-site. Additionally, the system allows the developed design model to be fabricated with holographic instructions. In this paper, we present the concept and workflow of the developed system, as well as its deployment and evaluation through an experimental case study. The outlook questions how such systems could be transferred to current design and building tasks and how such a system could reduce delays, avoid misunderstandings and eventually increase building quality by closing the gap between the digital model and the built architecture.

**Keywords:** mixed reality, virtual reality, interactive design, collaborative virtual environments, remote collaboration, immersive virtual environment.

## 1 Introduction

In recent years, there have been remarkable advances in mixed-reality technologies for architecture, engineering, and construction (AEC). Most augmented and virtual applications in AEC focus on structured manual activities (Goepel 2020; Jahn et al. 2019; Fazel and Izadi 2018), more routine cases of information exchange such as quality assurance (Dietze, Jung, and Grimm 2021; Büttner et al. 2017), or design review (Liu et al. 2020; Zaker and Coloma 2018). Collaborative design activities or interdependent collaborative tasks, such as complex negotiation, task specification, and interaction, are, however, not yet sufficiently explored (Marques, Bernardo et al. 2021; Wang and Tsai 2011; Benford et al. 2001; McGrath and Prinz 2001).

Collaborative activities in the field of AEC can involve a plethora of different stakeholders with heterogeneous backgrounds and expertise. Furthermore, stakeholders can involve remote collaborators, ranging from on-site to off-site users. Especially for communication between remote users, knowledge transfer is critical for a successful collaboration, particularly for task decomposition, handover processes, and design revisions. Improved decision-making processes can enhance workflow efficiency and collaboration in the creative process as it supports the inclusion of expert knowledge.

Current computer-supported cooperative work systems (CSCW) focus on enhancing collaboration in AEC by providing users with diverse shared information. This information includes, for instance, access to shared digital context through common data structures and environments utilizing building information modeling (BIM) software such as *Autodesk Revit* or *ArcGIS*. Other systems provide access to shared administrative tasks such as project management platforms, e.g., *Microsoft* planning software or *Autodesk Navisworks*.

Current CSCWs are suitable for very distinct and asynchronous tasks that do not require extensive communication and collaboration between users. Their structure allows users to complete individual tasks and inform other users about their progress. Nevertheless, due to their task-specific structure, these platforms are relatively rigid and do not provide an environment that fosters an immersive communication and discussion platform between users. This lack of a communication environment can cause user frustration and inhibit creativity. Especially interwoven negotiated task activities require a more comprehensive range of communication between different stakeholders.

The research presented in this paper, "Extended Reality Collaboration" (*ERC*), aims to complement the functionalities of existing CSCW systems and groupware tools in AEC by providing workflows for not yet well-supported collaboration and communication tasks. This paper proposes a mixed-reality immersive collaboration system that enables bidirectional communication and data flow between on-site and off-site users, enabling them to operate together on a digital twin in a collaborative virtual environment (CVE).The workflow and functionalities of *ERC* have been applied and validated in an architectural scale prototype - a sticky note installation.

## 2 Background

Our work builds upon two general fields of research: collaborative virtual environments and augmented fabrication.

### 2.1 Collaborative virtual environments (CVE):

Churchill et al. (Churchill, Snowdon, and Munro 2001) define CVEs as distributed virtual systems that enable users to collaborate with a digital environment and with each other. Asymmetric CVEs (Grandi, Debarba, and Maciel 2019; Piumsomboon et al. 2017) support users with different input and visualization hardware, adapting to their various capabilities. *DollhouseVR* (Ibayashi et al. 2015) facilitates asymmetric collaboration between co-located users, one virtually inside the dollhouse using a head-mounted display (HMD) and the other using an interactive tabletop. Another asymmetric CVE of co-located users is *shareVR* (Gugenheimer et al. 2017), which uses floor projection and mobile displays with positional tracking to visualize a shared virtual world for non-HMD users. A system developed for geographically separated users is presented by Oda et al. (Oda et al. 2015), which supports a remote expert to assist a local user. The results showed that a local user understood task instructions faster when the remote user wore a VR HMD and demonstrated the task in virtual space compared to written annotations. Commercial software such as the *Wild* and *Iris VR* provide CVEs for multiuser object manipulation but do not link it with fabrication parameters and instructions and, therefore, miss out on streamlining the design and fabrication phase.

### 2.2 Augmented fabrication:

Augmented fabrication in AEC focuses primarily on guiding a craftsperson in a manual fabrication process (Nee et al. 2012). This guidance can be with audio instructions, projection mapping, or screen-based mixed-reality (MR). *Fologram* uses MR headsets to see virtual holographic 3D models in space and assist unskilled construction workers in complex fabrication tasks (Jahn et al. 2019). An example of a screen-based augmented-reality (AR) system is *Augmented Bricklaying* (Mitterberger et al. 2020). This system extends purely holographic AR with a context-aware AR system providing humans with machine precision by tracking objects in space. *IRoP* (Mitterberger et al. 2022) is a system that allows users to instruct robots via programming by demonstration and to preview generated designs on-site via projection-based AR. While the growing number of AR fabrication research shows the enormous potential of augmented fabrication, all the discussed systems are solely designed to be used in-situ. None of the above examples link a local user with a remote user.

## 3 Methods

Our *ERC* system aims to combine design and fabrication functionalities in a collaborative virtual environment and enhance communication between two geographically separated stakeholders. Consequently, the system not only converges on- and off-site activities but also integrates the processes of design development and physical fabrication into one virtual shared environment.

### 3.1 User scenario

*ERC* involves at least two different stakeholders with different expertise that are in different locations; one user is on-site, and the other is off-site (see Fig. 1). The on-site user, "MR-User," is equipped with a MR headset, whereas the off-site user, "VR-User," utilizes a virtual-reality (VR) headset. The MR-User represents an expert construction worker, craftsperson, or construction site manager. The role of the MR-User is to provide site-specific data, insight knowledge, and instruct manual fabrication. The VR-User represents a stakeholder such as an architect or planner who navigates in a digital twin of the construction site. The role of the VR-User is to request and receive on-site information and feedback on the design to adjust the design accordingly. Furthermore, the VR-User provides different design options and supervises fabrication. Both users meet in the virtual space collaborating synchronously.

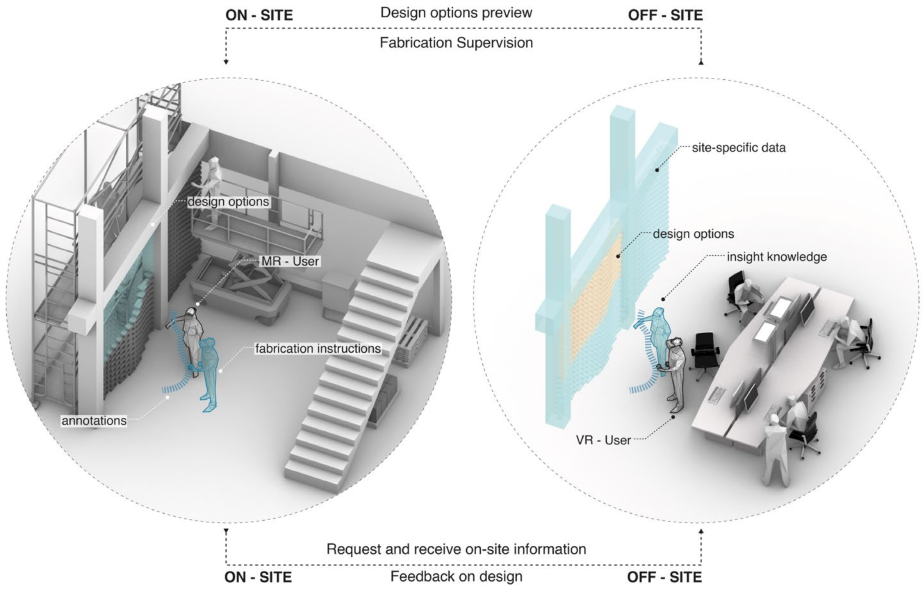
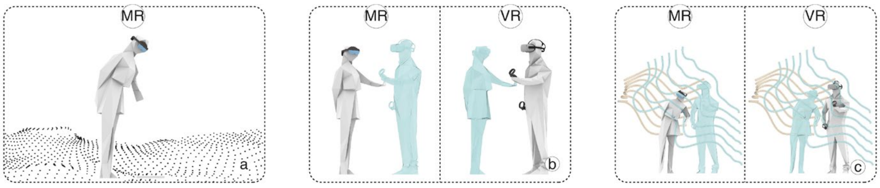


**Fig. 1.** User scenario showing the on- and off-site scenario with two distinct stakeholders

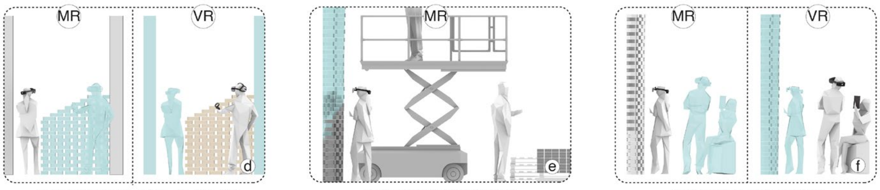
### 3.2 System Walkthrough

*ERC* is designed around two distinct phases, 1. Collaborative design phase, and 2. Augmented fabrication phase. In phase one, the VR-User (architect) and the MR-User (expert) evaluate the design options collaboratively. The MR-User localizes and creates the digital twin (see Fig. 2a), and then both users can meet in virtual space (see Fig. 2b). The MR-User sees the design options as holographs on-site, while the VR-User sees them in the digital twin of the construction site. The collaborative design phase has two distinct features: 3D sketching and annotating (see Fig. 2c), and collaborative design on-the-fly (see Fig. 2d). Phase two allows the users to plan and fabricate the design and has two features: holographic fabrication (see Fig. 2e) and fabrication supervision (see Fig. 2f).

To illustrate a typical interaction, we consider the user scenario described in section 3.1. The users follow a linear sequence of interactive design and fabrication sessions.



localize and create a digital twin meeting in virtual space 3D sketching and annotating



collaborative design on-the-fly holographic fabrication fabrication supervision

**Fig. 2.** System walkthrough.

### A - Creation of a digital twin:

The creation of a shared digital twin model featuring both the construction site as well as as-built model can be done in two ways, resulting in meshes with different resolutions. The first option is asynchronous, creating a high-resolution point cloud using a Lidar scanner. The second option is synchronous using the spatial awareness system of the MR headset. This option can be accessed in *ERC* via the 'scanning' feature allowing the users to receive a current as-built mesh of the construction site with customized levels of detail. This feature consists of several interactive modes to further access and edit the generated spatial data. The MR-User can select and send meshes to the VR-User. Based on these meshes, the VR-User can adjust and update the design options.

### B - Localization and meeting in virtual space:

Both users need to be localized in physical and virtual space to correctly send correlated spatial, geometric, and temporal data. Therefore, the local coordinate systems of the MR and VR spaces need to be aligned using relative transformation. The transformation requires the current position of each user relative to an origin frame. As an origin frame, the MR-User scans a referenced QR code in the physical space and then transmits the frame data to the VR-User. To share a mutual sense of presence, both users appear as avatars. The avatar position is updated in real-time and allows the users to communicate via hand movements and body motion trajectories.

### C - 3D sketching and annotating:

After localization and setting up a digital twin of the construction site, both stakeholders use a sketching and annotating feature to draw in 3D, highlight specific target areas or annotate existing designs (see Fig. 3). In this phase, both users can discuss potential design problems with the construction site's current as-built state.

### D - Collaborative design on-the-fly:

This feature allows users to preview and adjust a parametric design model on-the-fly in MR and VR and directly preview it as a hologram in-situ (see Fig. 4). The VR-User loads the parametric model using *Rhino.Inside*[1] and adjusts the parameters of the digital model according to the feedback of the MR-User. The VR-User has access to properties of the parametric model and can adjust these parameters in near real-time. Both users can sketch directly on the design options using the "3d sketch and annotate" feature.

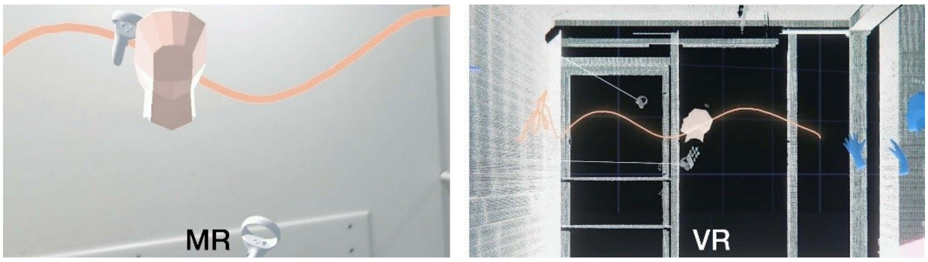


**Fig. 3.** 3D sketch and annotation feature. On the left is a first-person view of the MR-User watching the VR-User sketch. On the right side is a third-person view of the MR and VR-User drawing collaboratively within the VR space.

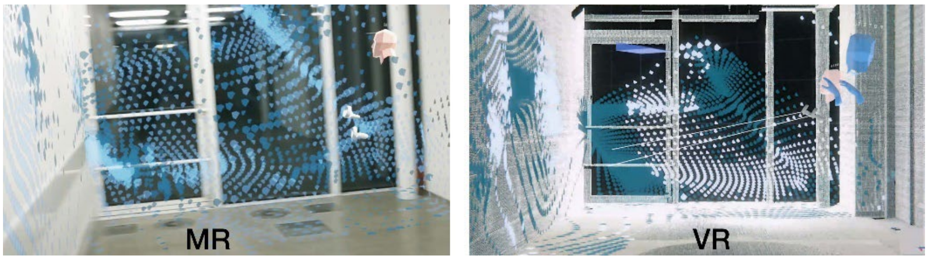


**Fig. 4.** Collaborative design on-the-fly feature. On the left is a first-person view of a hologram of the design on the installation site. On the right side is a third-person camera view of the MR and VR-User discussing the design in VR.

### E - Holographic fabrication:

After deciding on a final design, the users switch from the interactive design phase to the fabrication mode (see Fig. 5). The fabrication mode can also include multiple other users as the system can be deployed on various augmented reality devices. The MR-User receives fabrication-specific information such as the holographic 3D model, estimated fabrication time, and the number of elements deployed. Furthermore, the MR-User can switch between fabrication sessions. These sessions are visualized in different colors representing the estimated daily working hours (see Fig. 6-2).

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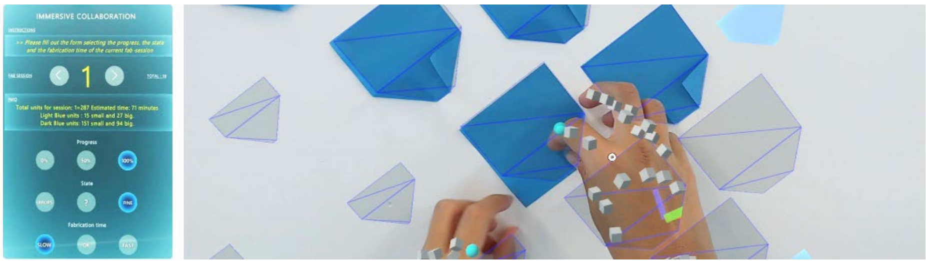
[1] Rhino.Inside® is an open-source project which allows Rhino and Grasshopper to run inside other 64-bit Windows application

**F - Fabrication supervision:**
This mode allows the MR-User to enter information about completed tasks, current fabrication sessions, and problematic areas. Furthermore, the VR-User can virtually join the fabrication session to supervise the process (see Fig. 6).



>> Please fill out the form selecting the progress, the state and the fabrication time of the current fab-session

Total units for session: 1=287 Estimated time: 71 minutes
Light Blue units : 15 small and 27 big.
Dark Blue units: 151 small and 94 big.

**Fig. 5.** A menu informing the MR-User about fabrication parameters and the holographic 3D model supporting fabrication.

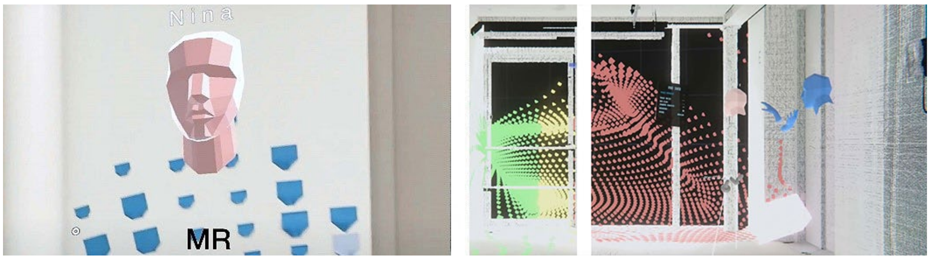


**Fig. 6.** Fabrication supervision feature. On the left is a first-person view of the MR-User looking at the VR-User. On the right side is a third-person camera view of the MR and VR-User discussing the fabrication in VR. The different colored elements show the different fabrication sessions.

## 3.3 System Architecture

As displayed in Figure 7, the system architecture consists of three main parts: (1) an on-site MR setup with a scanning system, (2) an online server, and (3) an off-site VR setup. The on-site MR setup consists of a laser scanning device (*Leica RTC 360*) providing high-resolution on-site scans, an MR-headset (*Microsoft Hololens2*), a laptop, and a WIFI router. The off-site hardware consists of a VR headset (*Oculus Quest 2*), a laptop, and a WIFI router.

The software setup is structured as follows. Two autonomous *Unity3D* applications were developed, one for MR and one for VR. The MR application uses the Mixed reality toolkit (*MRTK*) and *OpenXR* library to enable spatial awareness scanning and QR-code detection. The VR application is developed using the *OpenXR* library. Furthermore, *Rhinoceros3D*, *Grasshopper*, and Python are used to create algorithmic designs. *Rhino.Inside*, enables compatibility and bidirectional communication between external *Unity* processes and *Grasshopper*. The online communication is based on the Robot Operating System (*ROS*) (Quigley et al. 2009). The rosbridge package is used to access the publish-and-subscribe architecture of *ROS* and *ROS#* for the *Unity3D* applications.

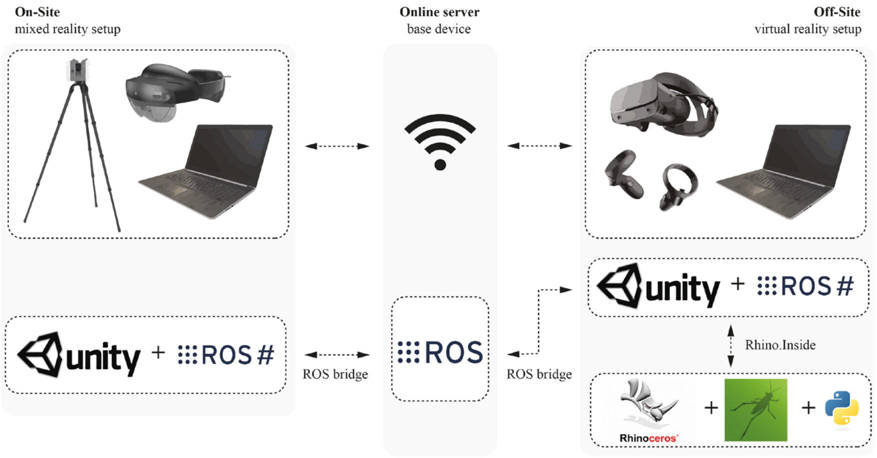


**Fig. 7.** System architecture

# 4 Case Study

To validate the feasibility of the proposed method and demonstrate the potential for a concrete fabrication system such as façade panels, we focused on one full-scale experimental implementation. For a user-friendly experience, the user interface (UI) design was based on each user's different roles and work packages (see Fig. 8). We used sticky notes as placeholders to showcase the various and complex types of information that can be exchanged between two geographically separated users. This information includes the position (P), rotation (a), size (f1), geometry (folding type) (f2), and color of each unit (see Fig. 9).

The total fabrication time was 26 hours, whereas the interactive design was around 1 hour. The final design was fabricated using two MR headsets, and a total of 4000 sticky notes were placed. The final design was split into distinct fabrication sessions of 60-90 minutes. We used an attractor-based approach for the computational design, which influenced the design depending on its location in space and its distance from physical boundaries (see Fig. 10). Specifically, the attractor's location (CP) changed the position, rotation, color, size, and folding type of the sticky notes. In our case study, the sticky note's location was projected onto the spatial mesh data (M) scanned by the MR User. This projection resulted in a precise position for each sticky note on the as-built data of the installation site. During the design phase, the VR-User moved the attractor as an interactive 3D prism in virtual space to control the number of projections. The VR-User could adjust the design parameters collaboratively with the MR-User while the MR-User saw the different results as holographs in-situ. Furthermore, the MR-User could interact with the design via sketching to adjust the outline of the design. After agreeing on a final design, the MR-User fabricated the full-scale experimental implementation (see Fig. 11) while the VR-User supervised and informed the process.

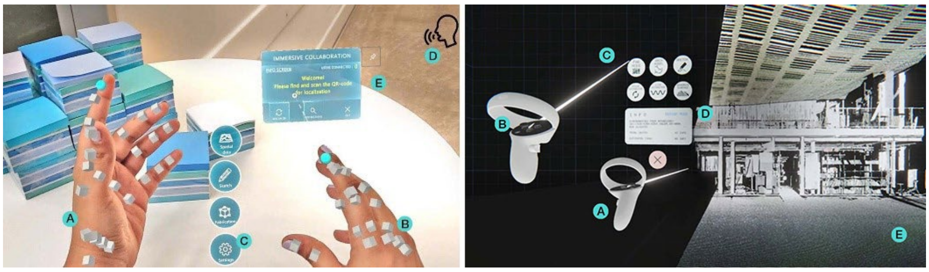


**Fig. 8.** Left: The MR-User interacts via hand tracking (A), gesture tracking (B), menu buttons (C), and voice commands (D). The MR-User sees an info window superimposed over their view (E). Right: The VR-User navigates the space and interacts via controllers (A) using controller buttons (B) and virtual menu buttons (C). The VR-User sees an info screen (D) and moves within a digital twin of the construction site (E)

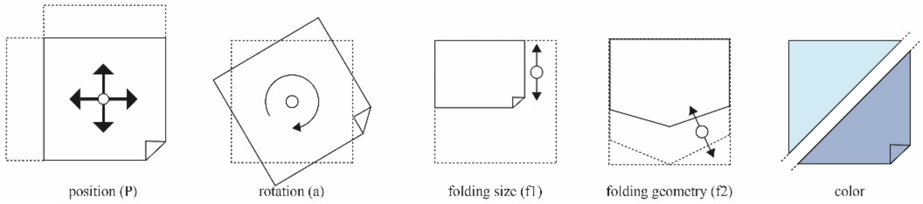
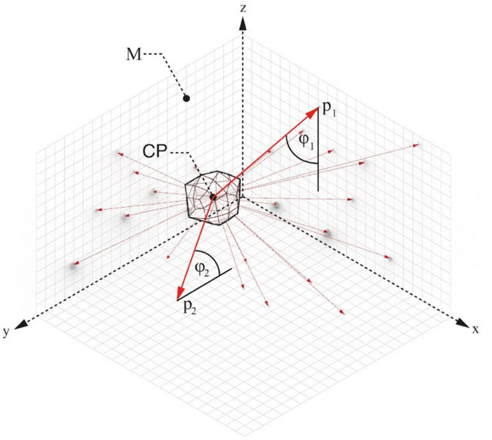


**Fig. 9.** Various and complex parameters that can be exchanged with the system



| Design Paramters | |
|---|---|
| CP | centerpoint of attractor |
| p1, p2 | intersection point |
| [φ1,φ2....] | angle |
| M | scanned mesh |
| P | sticky note position |
| a | sticky note rotation |
| f | sticky note folding size |
| color 0,1 | sticky note color |

| Remapping values | | |
|---|---|---|
| P | = | p |
| a | = | φ |
| f | = | remapped value of φ |
| φ < tolerance | = | color 0 |
| φ > tolerance | = | color 1 |

**Fig. 10.** Computational attractor-based design logic and remapping values to determine sticky note position, rotation, folding size, and color

# 5 Results

Our *ERC* system allowed for an intuitive and real-time design interaction for users in different physical locations. The users had access to a full-scale impression of the architectural model augmented and contextualized by site-specific information. Both users collaboratively designed and fabricated a complex and full-scale architectural installation (see Fig. 12). Furthermore, personalized communication was achieved by creating avatars for all users. Implementing the *ERC* system and the case study provided us with insights into the hardware and software limitations.

**Fig. 11.** Photograph of the fabrication of the final physical installation.

**Fig. 12.** Photograph of the final physical installation.

### 5.1 System limitations

We experienced hardware limitations regarding the environmental scanning and localization as well as jitter of the digital model (see Table 1). The main software limitations were delays and transmission speed, especially between the Grasshopper environment and the Unity interface with increased mesh count and internet connection speed. To avoid delays between the MR and VR-User, we used a mesh resolution of 20 triangles per cubic meter. Furthermore, the system still has a limited amount of drawing tools in the “3D sketch and annotation” feature. Extending the drawing tools would allow users to interact with a broader range of communication options. In noisy environments, it was difficult to get the other user's attention. Therefore, it would be essential to implement an "attention feature". Additionally, the current system lacks a “documentation feature” that would allow users to upload video, pictures, or voice memos to the digital model with associated location. Such a note collection could help on-site workers keep track of construction site notes and allow easier communication with off-site users. These notes could also be read asynchronously, allowing users to log into the system at different moments.

| QR – Code distance | Drift of the digital model |
|---|---|
| < 0.45m and in view | 0.1 - 0.3cm |
| ~ 4m and in view | 1.5 - 2.3cm |
| not in view | 2 - 3cm |

**Table 1.** Relation between QR Code placement and visibility and drift of the digital model. The QR code dimensions were 12.5cm x 12.5cm.

## 6 Conclusion and Outlook

This research investigates the potential of collaborative design activities and how they could lead to better knowledge and information flows between on-site and off-site stakeholders during design and fabrication processes. The functionalities of the system were evaluated via a full-scale case study, aiming to define collaboration protocols and improve interaction and communication. Even though there are still limitations, this research shows the potentials of such a system to improve supervision and collaboration between on-site and off-site stakeholders, such as architects and construction supervisors, to support a paperless construction site. The key findings of this research are novel collaborative MR and VR interfaces, 3D workspace scenes with sufficient context-awareness, and a fabrication protocol that includes remote monitoring and planning. As an outlook, such a system could be applied towards detecting deviations between the as-built and the digital model in order to decrease project costs and building time. Such a system could be applied to real building scenarios, i.e., on-site construction meetings, custom interior designs, renovations, and complex building elements. *ERC* allows dispersed personnel to have more direct contact, thereby reducing problems of isolation and miscommunication. Furthermore, such a system could accelerate workflows and support a teleoperated construction site.

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## 8 Author’s contribution

DM wrote the manuscript, did the conception of the work, and supervised the thesis. EA and FS developed the system as part of their MAS master thesis. EA contributed to research for the manuscript. RR wrote the manuscript, did the conception of the work, and supervised the thesis. LV was part of the supervision of the thesis. FG and MK contributed to the conception of the work. All authors reviewed the manuscript.

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