Facilitating Synchronous Remote Collaboration on On-site Architectural Design using Mixed Reality

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Summary: Developments in Extended Reality (XR) technology help push the boundaries of design prototyping. In the context of architectural design, one area which has recently attracted design researchers is that of on-site design. Essentially, designers are found on-site while wearing a head-mounted display (HMD) and seeing virtual content projected on a physical site. For example, one may stand in New York City in front of an empty plot and "see" a virtual skyscraper to be built in the future. Despite the excitement around the potential of such systems to enhance design activity, their realization poses various challenges. For one, computational resources on-site are usually limited, and thus so are the possibilities for manipulating the design in real-time. One potential solution for this is to offload some tasks to a remote site. This paper reports on the results of a pilot study conducted with such a system. Two collaborators, one found in Okinawa (on-site) and another in Tokyo (off-site), interacted and designed a building on-site. User feedback has yielded insights regarding the design and implementation of remote collaboration systems as a potential solution for immersive on-site design.

Keywords: Extended reality; collaborative design; remote communication; on-site design; tele-existence.

1. Introduction

With the rise of Extended Reality (XR) technologies, new possibilities are available for design prototyping[1]. For instance, Virtual Reality (VR) technology enables us to visually experience the design product in a realistic manner prior to its construction and can thus support decision-making in design. Similarly, Mixed Reality (MR) enables us to understand existing products better, without the need to manufacture them or experience them in a physical form[2)3)]. One exciting possibility which is being explored recently is that of on-site design in XR. Systems for on-site design are being developed for architectural design[4], with the aim of enabling architects to prototype and test their ideas in-context and on-the-fly. These systems can alter the ways in which we will design in the future.

One core issue with developing on-site design systems is that on-site design demands fast information processing. The designer on-site thus needs to (a) be equipped with a portable processor capable of this, and (b) to have sufficient control on-site. Both the former and the latter pose practical difficulties for realizing on-site design in-practice. The first difficulty stems from hardware limitations, such as limited battery and computing power in currently available head-mounted displays (HMDs). The second difficulty stems from software limitations, such as lack of suitable CAD platforms for facilitating this activity. Therefore, to enable on-site design, new solutions are required both in terms of XR hardware and software.

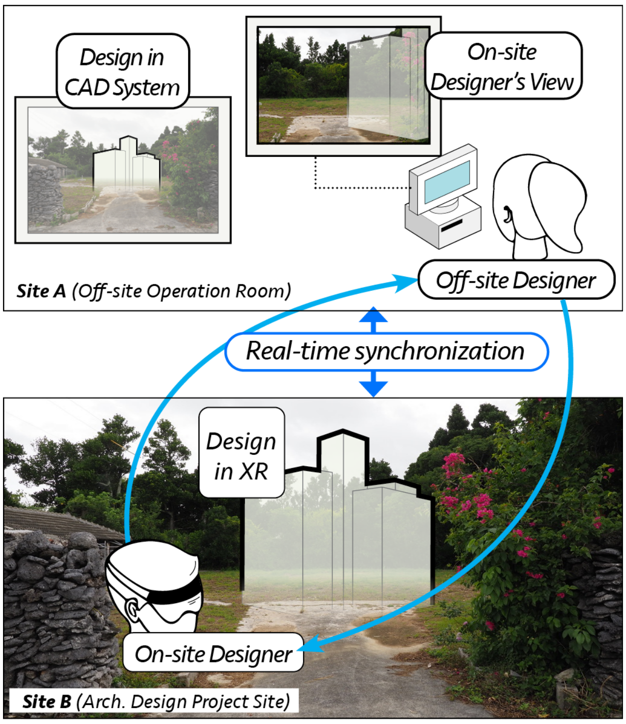

Figure 1. Setup overview.

Addressing the above, an environment for on-site design is proposed and tested, by offloading some of the information processing and control to a remotely situated collaborator. The on-site designer (OSD) and the remote designer (RED) situated off-site together form a "hybrid team" (Figure 1). The system is

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presented and key challenges in its development are described. Based on these, recommendations for further development of such systems are discussed.

2. Remote Design Collaboration in XR

Design commonly involves several stakeholders, each contributing from their own perspective and skills to the design process. Scenarios in which not all stakeholders can be co-located require to harness remote communication technology, to facilitate remote design collaboration. Partly due to processes of globalization, such solutions are attracting attention in the design computing community. Khajehee et al., for example, have responded to the lack of ability to collaborate in real-time on computational design projects by developing a tool which facilitates this. Their tool ("RemoSharp") enables collaboration of participants at different skill level and improves group work.[5]
XR technologies can support creators in a variety of fields and domains, such as product design[6], circular design[7], architecture [8] and even art[9]. Among its key strengths is its contribution to enhancing prototyping processes[1], by overlaying virtual information onto physical objects/environments. In architectural design, where the physical environment consists of a site used for designing, XR can help to uncover tacit knowledge regarding the site[4]. The above imply on the potential of XR to support prototyping in on-site architectural design activities.
When XR is used for collaborative design activity involving the actual site, it is not always possible for all parties to be physically present on-site. Therefore, it is important to develop solutions for such asymmetric collaborative scenarios, where some stakeholders are on-site and others are off-site, and are potentially using different devices to join a single session; see Pereira et al.[10]. In other words, we need to develop solutions for remote collaboration of hybrid teams.

3. Motivation, Research Question and Objectives

3.1. MOTIVATION

While idea of utilizing XR environments for remote collaboration is at least two decades old[11], systems for remote collaboration are continuously being sophisticated by drawing on state-of-the-art technologies in XR, depth sensing and more[12]. In contrast with the growing interest in such systems, information regarding their *development process* and the challenges they entail is scarce, and is mostly available in informal sources such as private blogs etc. Therefore, researchers interested in their development find it difficult to predict and tackle potential issues effectively. This paper provides readers with a concise yet valuable account of several challenges which may arise in developing a remote design collaboration system in XR. By sharing the experience of different types of users we increase the awareness of potential issues, as well as suggest possible ways to address them. This furthers the efforts for developing remote collaboration XR systems for the benefit of future designers.

3.2. RESEARCH QUESTION & OBJECTIVES

Based on the above, our research question is formulated as follows: what are the main challenges in facilitating effective XR remote collaboration in hybrid teams?
Our main research objectives in this pilot study are:

- design and implement a system for facilitating synchronous remote collaboration, and
- test the system to derive insights regarding future development, for supporting remote collaborative design.

This study focuses on an architectural design scenario, as a typical example of on-site design. However, its findings may be relevant for other contexts in which a designer has to develop a design prototype without the capacity for intensive computation or comfort available in an office setting, where one can use a powerful workstation for several hours to complete a given task.

4. Method

4.1. SYSTEM OUTLINE & IMPLEMENTATION

The system (S) is composed of four sub-systems (s1-4; Table 1). All visual content describing the site (prepared offline) and the design product (created online) is managed in (s1). The visual content created in (s1) is reflected automatically and continuously in (s2), through a networking system (s3) which links (s1) and (s2). Simply put, a change in (s1) initiated by RED , such as moving an existing object or creating a new one, triggers a change in (s2), and thus seen by OSD. Next, (s4) is used for transferring visual data from OSD to RED, by streaming the content of their HMDs in real-time, as well as transmitting audio between the parties.

Referring to Table 1, HOSTapp and CLIENTapp were implemented using the real-time engine Unity. The former was deployed on a commercial workstation equipped with an Nvidia GTX 1080 graphics card, and the latter on a Microsoft HoloLens 2 HMD. The workstation was situated in a lab setting in Tokyo and used by RED, with access to a local area network. The HMD was worn by OSD in Okinawa, with cellular internet access through a portable Wi-Fi device. OSD was also equipped by a generic laptop device connected to the same network. This device enabled audio-visual communication (AVcom) using Zoom, which was also deployed on the workstation in Tokyo. NETapp was also implemented in Unity (using Unity Relay service) as a sub-component of both CLIENTapp and HOSTapp, thereby enabling to share MR content between the parties (Figure 2).

Table 1. System decomposition into four sub-systems

ID	Name	Description	User
s1	HOSTApp	Off-site 3D environment	RED
s2	CLIENTApp	On-site XR Visualizer	OSD
s3	NETApp	XR Networking system	Both
s4	AVCom	A/V transmission system	Both

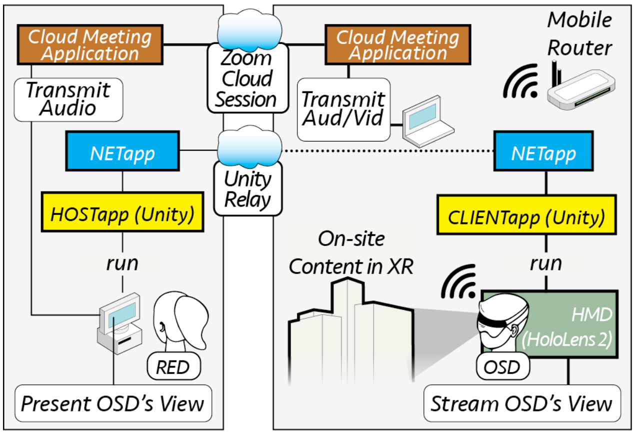

Figure 2. System implementation.

4.2 TASK, MATERIALS AND DATA COLLECTION

To test the system, a simple task of exploring alternatives to a design proposal was devised. A model of a traditional Japanese residential house was constructed prior to the experiment using a CAD environment (Rhinoceros 3D) and inserted into HOSTapp and CLIENTapp, so that both RED and OSD could view it simultaneously; the former in a lab setting and the latter on-site (Figure 3). The site chosen for the activity is an empty plot of land in the island of Izena, found in Okinawa (Japan).

The designers were requested to use the system to explore potential additions to the building. Requests were for adding elements to the design were made verbally by OSD (e.g. "please extend the roof") and fulfilled by RED, to the best of their ability. The changes were then examined by OSD, based on their impression of the design result on-site. Therefore, the task can be seen as a cycle of generation and testing of design alternatives[13) - generation is requested by OSD and fulfilled by RED, then tested by both (and especially by OSD on the basis of the on-site experience of the result).

RED's screen as well as OSD's HMD visual content were recorded. A total of three sessions were held, resulting in above 5 hours of recorded data. The videos recordings were reviewed by their respective users, and comments regarding challenges and opportunities were extracted from the documentation, based on the conversation between the parties and the visual content of their displays.

Figure 3. Building model in MR from the perspective of OSD.

5. Results from a Pilot Study in Okinawa, Japan

Insights regarding the usability and potential of the system to facilitate effective remote collaboration were identified. We introduce these from the perspective of OSD (4.1), as well as from the perspective of RED (4.2).

5.1. USER EXPERIENCE OF OSD

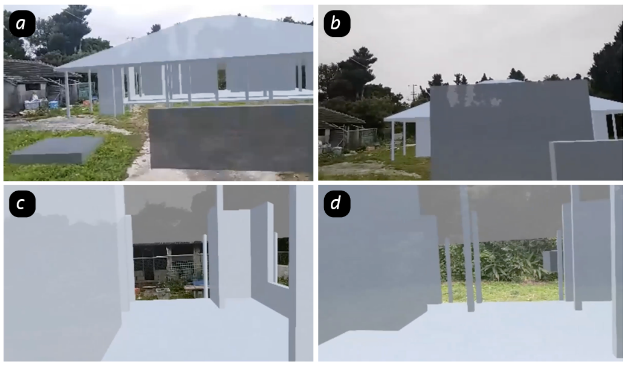

Figure 4. HMD Captures from OSD: (a-b) exploring the addition of surrounding walls in different heights; (c-d) exterior physical environment framed by virtual model.

Insights from the perspective of OSD are given below in four categories: general impression, sense-of existence, sense of use and other technical issues.

- **Impression:** OSD has found the experience of walking around the site realistic. When looking at the full-scale model of the building projected visually, the viewer senses that the building is "there". However, the building is only "there" in the sense that the visual stimulus from the site is merged with that of the light signals projected by the HMD. Therefore, OSD found the experience of taking off the HMD and seeing the virtual model vanish into thin air somewhat unusual. Such moments provide designers valuable, albeit brief, opportunities to see the site afresh.
- **Sense of Existence:** OSD interacts with the full-scale model of the virtual building as if it is both a real and a virtual building, despite being aware that the projection is only virtual. OSD tends to be interested in the substantial structure of the design. For example, he expects that the

roof frame or the ceiling can be seen when looking up inside the model. At the same time, he is conscious of the gap between the perceptual experience of physically walking around in the real space and the perceptual experience of seeing the model as mixed reality. There are incongruencies between the virtual model which invites one to step up/down (e.g., to stand on the balcony) and the floor of the physical site which is almost flat. The feeling of material such as texture, weight, density, shade, and shadow, etc. is also important when OSD interacts with the 3D model as if it were a real substance. These suggest that it is important to devise a way of projecting a full-scale 3D model in MR, i.e., the level of abstraction, granularity, resolution, precision, and selection of the contents projected, should be adjusted such that OSD's interaction with them meets their expectations.

- **Sense of Use**: reducing latency in remote interaction is of critical important for facilitating effective remote collaboration. Time lags between a simple design operation, such as movement of an element, and confirmation of the result are expected to be short. Additionally, it is important to increase the transmission rate and to control the data amount transmitted to fulfill the expectation or intention in the interaction. Furthermore, it is essential to maintain a correspondence between the real site and its abstracted model on which the artifact projected. The origin and axes of the real environment and those of the projected design plan require adjustment.
- **Other Technical Issues:** First, glare prevented clear vision for OSD. It is essential to improve the visibility of the visual content when an actor on site visually examines the virtual 3D model displayed in the HMD under a bright sky. On a bright day, forms often appear pale and unintelligible, even without direct sunlight. This also decreases the sense of immersion that relies upon seamless blending of the virtual content with the physical scene. It is also required to prevent overheating of the HMD when used in a hot environment. Second, we identified a tendency of the HMD to overheat and malfunction under direct sunlight. Relatedly, it was observed that the HMDs battery life was too short and insufficient for facilitating a comprehensive discussion of the design (less than 1 hour). Third, logging into the session required OSD to type a login passcode using a virtual keyboard, which was extremely time consuming and ergonomically difficult in outdoor conditions. Fourth, it was difficult for OSD to reliably receive the passcodes by audio.

5.2. USER EXPERIENCE OF RED

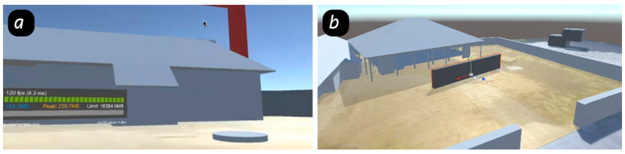

Figure 5. Screen captures from RED: (a) virtual model at eye level; (b) virtual model during addition of a new wall element from a bird's eye view.

Insights from the perspective of RED are given below, using the categories introduced in the previous sub-section:

- **Impression:** using the system off site on a flat screen feels somewhat similar to the experience of playing a computer game. Virtual objects such as rooms, balconies etc. are available and can be placed "on" the site virtually, as one desires. The fact that the visual result cannot be expected by RED motivates him to try various options in a playful manner. Furthermore, not only that it is difficult to imagine the result of placing a virtual object in the real scene, but it is also difficult to predict the experience of OSD and his response to changes made to the model, and especially to changes which were independently initiated by RED.
- **Sense of Existence:** while not being present on-site, RED does experience the result as real in some sense, based on the visual information received from the HMD of OSD. This is especially the case when the virtual model of the site and the real site are aligned, and newly added objects appear in their intended scale. However, since the visual information of the MR display is relayed to RED in 2D as a real-time video stream, the sense of three-dimensionality is lost, resulting in a less immersive experience from that of the on-site collaborator.
- **Sense of Use**: similarly to OSD, RED has had difficulties caused by latency as well. For instance, RED may request to move a virtual room to the left, and then say "stop now"; however when examining the result on-screen, RED may have doubts regarding the successful positioning of the room. This sufficient correspondence between the audio and visual information must be maintained to facilitate effective real-time collaboration. Furthermore, since RED is equipped with abilities render OSD as dependent on him, RED perceives his role as somewhat of a supporter rather than a designer. At the same time, the freedom of RED to add and manipulate forms in the scene allows him to actively participate in the design process. Additionally, since RED could not control his view, he was limited to seeing the site from the perspective of OSD. This caused

asymmetry in the understanding of the space, as one user was essentially controlling the visual content displayed to the other. Therefore, it limited the ability of RED in two important ways – in his ability to intervene and add elements, as well as in his ability to explore proposed design solutions from multiple angles, as needed. Under these circumstances, a specific type of interaction evolved in which RED requested OSD to adjust their position and orientation in the physical space, in attempt to get the "right" angle for viewing. This is both inconvenient from the perspective of the two parties as well as ineffective (focusing on a single task at the same time does not enable working in parallel).

- **Other Technical Issues:** Additional technical issues with the system were observed off-site as well, albeit to a lesser degree. First, with respect to networking, the lack of ability to verify the connection of OSD to the session made it difficult to engage in the activity, since manual tests needed to be made prior to designing instead (i.e., by moving an object in one scene and confirming the response in the other). Second, naturally, difficulty with communicating the passcode by audio were observed from RED as well. Third, RED found it hard to grasp the position and view of the site from the video, so calibration and positions of the hologram was extremely difficult.

6. Discussion

The results suggest several topics for consideration when developing general systems for remote XR collaboration, and specific ones for on-site design, discussed below.

First, considering that RED and OSD have access to different technical features when using the system, roles for each naturally emerge during the activity. The distribution of roles should thus not be left to chance or accepted as by product of using such systems. Instead, we recommend that the role of each of the parties is clearly defined in advance, and that the features which are available to him/her serve their specific purpose in the collaborative activity.

Second, the above asymmetry projects onto other parts of the collaborative activity and raises further important points for consideration. Among these, the lack of independence of RED in determining their position and orientation when viewing the space seems especially problematic, as it both creates a dependency between the users (which may be undesirable), as well as takes a toll on the efficiency of the team (due to interference with parallel work). collaborative activity. One way to address this is to equip RED with remote control over a robotic system which is found on-site, as a form of tele-existence with mobility capabilities [14], such that they can position it to capture the view of the space that is relevant to the task at hand. Another way would be to scan the site in advance (using a 3d scanner or photogrammetry) and place it within the virtual environment off-site. In this way, when RED examines objects added on their display they will see them in context. These solutions can also enable RED to view the scene from any angle they wish, which is important for imagining the actual result on site. Readers can compare these proposed solutions with merely viewing the content using a highly simplified, non-realistic model (Figure 5). Extending the above suggestion, we believe it may be beneficial for RED to have access to MR content as well, in addition to manipulating the design on a flat-screen display. While the latter has its advantages (e.g. simplicity of operation), an MR display for RED can help reduce the gaps in experience between the collaborators, and thus be beneficial in facilitating effective communication between the parties. Note that communication may also be enhanced via other technological means, such as via real-time gaze sharing in MR.[15]

Third, awareness of environmental conditions is critical for on-site collaboration. This includes weather aspects such as rain etc., as well as daylight conditions which can impact the legibility of the display and even lead to hardware failures. Since environmental conditions are not entirely predictable, ways to cope with these difficulties should be developed on multiple fronts. The authors have found, for example, ready-made templates that enable one to create custom-made shades for improving the visual quality of the HMD in bright environments.[16] In the future, we hope that such considerations will be integrated into the hardware of HMDs and enable smooth outdoor MR experiences. Similarity, to address the problem of overheating, simple solutions can be utilized, until the state-of-the-art hardware is improved by the manufacturer. For instance, wearing a head cover in the form of a large hat, to prevent direct sunlight from striking the device. Specifically with respect to HoloLens2, such solutions are essential, as the device fully relies on passive cooling, and thus does not respond fast enough to heat coming from a direct source such as sunlight hitting the processing unit.

Fourth, it is interesting to point out that the system not only enabled to examine potential design solutions on-site, but also to change the way one views the site in the first place. As pointed out by OSD, removing the HMD, enables one sees the site afresh. Although this visual effect is a byproduct of using MR, it suggests a fascinating option – rather than focusing only on the addition of virtual content to the site, we can develop applications for helping the designers see *the site itself* in a new way, by making changes to the environmental conditions. For example, we could dig a hole in the ground, which may then invite the addition of architectural elements that would not be considered when the ground is flat. Therefore, we recommend that such systems offer users the possibility of visually manipulating the site, and not only the virtual elements added onto it.

Finally, expanding upon the above recommendation, we should remember that the ability of MR to reliably create an immersive experience is limited. As pointed out by our OSD, he could see the virtual buildings floor (which was higher than the actual ground) but could not fully experience the building's interior reliably (being unable to step on the indoor floor, as it is above ground). Considering this, it may be beneficial to integrate our system with a VR system, which takes over the display and shows immersive content that overrides physical reality, as needed.

7. Conclusion

A system for remote collaboration in architectural design prototyping was implemented and tested. Two remote collaborators, one on-site and one off-site, used the system and commented on their experience, as a pilot study. The study suggests several promising directions for developing computational systems for remote collaboration in XR design prototyping and for on-site design.

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