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ORIGINAL PAPER

Exploring interaction techniques for 360 panoramas inside a 3D reconstructed scene for mixed reality remote collaboration

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Abstract

Remote collaboration using mixed reality (MR) enables two separated workers to collaborate by sharing visual cues. A local worker can share his/her environment to the remote worker for a better contextual understanding. However, prior techniques were using either 360 video sharing or a complicated 3D reconstruction configuration. This limits the interactivity and practicality of the system. In this paper we show an interactive and easy-to-configure MR remote collaboration technique enabling a local worker to easily share his/her environment by integrating 360 panorama images into a low-cost 3D reconstructed scene as photo-bubbles and projective textures. This enables the remote worker to visit past scenes on either an immersive 360 panoramic scenery, or an interactive 3D environment. We developed a prototype and conducted a user study comparing the two modes of how 360 panorama images could be used in a remote collaboration system. Results suggested that both photo-bubbles and projective textures can provide high social presence, co-presence and low cognitive load for solving tasks while each have its advantage and limitations. For example, photo-bubbles are good for a quick navigation inside the 3D environment without depth perception while projective textures are good for spatial understanding but require physical efforts.

Keywords Mixed reality · Remote collaboration · 360 Panorama · 3D scene reconstruction · Interaction methods

1 Introduction

Remote collaboration techniques can enable a local worker to collaborate or receive help from a remote expert from different locations. For example, video-conferencing can be used to share audio and video cues between remote workers. Mixed reality (MR) technologies, such as overlaying virtual annotations on a view of the real world [1,2] can improve collaborative performance by using natural visual cues for nonverbal communication.

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Using augmented reality (AR) to enable the remote expert and local worker to share avatars [3–5] , view awareness cues [6,7], make gestures [8], and point [9] or draw on the local worker's environment [10] makes otherwise difficult tasks easier to solve.

In addition to sharing visual cues, using virtual reality (VR) to share a view of the local worker's environment could also improve collaborative performance. A local worker can stream from a 360 camera [11] or 3D reconstruction using a depth camera [12] to share his/her environment to the remote expert. The remote expert can use VR technology to immerse themselves into a virtual copy of the local worker's environment and collaborate. This enables the remote expert to work independently without relying on the local worker for view perspective control, as is done in a standard video-conferencing configuration [13].

Although MR remote collaboration could help in solving complicated tasks, there are still limitations. For example, capturing and sharing the environment using a 360 camera provides a high-resolution image with relatively low bandwidth, but restricts translation movement of the remote expert. The 3D reconstruction allows the remote expert to have a fully independent control of the view perspective, but at a lower visual quality as a trade-off. In addition, sharing 3D environments for MR remote collaboration could also be challenging too as it requires processing time and space for physical movement. In recent years, several techniques combining the two have been proposed. A remote expert worker switch between a 3D environment and live spherical 360 video to collaborate with the local worker from different perspective [14] or interact with 360 panoramic images that embeds on the 3D environment to achieve asynchronous and synchronous collaboration [15]. However, this is still a new area of work with some limitations such as high learning curve requirement that affects system usability, and how it can affects user behaviour in a remote collaboration.

In this paper, we present an evaluation study that focused at the performance and user behaviours when collaborating using a hybrid MR remote collaboration system. We revised and made enhancement at a prior work that embeds 360 panorama images into a hybrid prototype system [15] by introducing a projective texture technique that allows the remote expert to preview at different 3D vantage points of the local worker's environment. This creates an opportunity to investigate the advantages and disadvantages of different interaction techniques in a hybrid system. The paper also aims to explore some of the existing research gaps and limitations in the current MR remote collaboration system configurations as mentioned above. In the rest of the paper, we first review the related work and the current research gaps. Then, we describe our prototype configuration and its features followed by the setup of our user study. Next, we discuss our user study results and findings. Finally, we summarise our findings in the conclusions and future work.

Compared to existing work, this paper makes a number of key contributions:

1. A novel MR remote collaboration technique which integrates 360 panorama images into a 3D reconstructed scene as photo-bubbles and projective textures.
2. A user study that compares the representation of the immersive experience using a 360 panorama against the projective texture mapping of a 360 panorama into a 3D reconstructed scene.
3. A user study on 360 and 3D MR remote collaboration that investigates task scenario including both inside-out and outside-in task space configurations.
4. Design suggestions for developing a MR remote collaboration system that merges 360 panoramas with a 3D reconstructed scene.

2 Related work

There are many benefits of using MR for remote collaboration. It enables visual and contextual sharing between two separated workers, enhancing Social Presence [9] and improve task efficiency [16]. However, with a variety of tasks, different configurations are needed to meet use case requirements. In this section we review related work in sharing 360 video and 3D reconstructed scenes.

2.1 360 Video sharing remote collaboration

In recent years, researchers started to explore how to share views of a user's environment in a simple and low-cost manner. With the advances in 360 cameras, Lee et al. attached a 360 camera on top of the local worker's head to share a full 360-° view to be used for MR remote collaboration [11]. Previously, this approach was made using multiple cameras attached around a user's head [17].

In early years, remote telepresence technology have been proposed by attaching camera(s) on a robot [18,19]. Following that, Schulz et al. [20] and Matsuda et al. [21] also demonstrated a few use cases of using a robot with camera to achieve remote telepresence that were inspired from a prior work. Tang et al. [22] conducted a user study investigating challenges and benefits of sharing an immersive remote experience using a 360 camera. They found that the system offered a number of unique benefits compared to a standard mobile video chat, especially in the quality of the immersive experience. This can also be affected by the 360 camera placement [23].

View sharing using a 360 camera also provides independent control of the viewing direction as the local worker does not need to control the view of the camera [24]. This has made solving tasks more efficient, especially with the integration of AR. For example, in a user study Lee et al. found that integrating view awareness cues into a remote collaboration system that shares the environment using a 360 camera can promote a user's collaborative experience, and sense of co-presence [25]. In a similar use case, Teo et al. found that adding more visual cues such as hand gestures, a virtual pointer and annotation drawing can further improve the sense of Social Presence [9].

These systems promote the ease of accessibility by sharing a 360° view of the local worker's environment with the remote expert. However, it only applies to certain environments. For example, sharing a 360 environment could be difficult in a complicated room structure where the remote expert could not travel independently within the scene to look around the corners or behind occluding objects. Also, measuring and understanding distance inside the scene can be impossible due to the lack of depth perception.

2.2 3D scene reconstruction remote collaboration

Sharing an environment using 3D reconstruction overcomes some of the limitations of 360 video sharing. It allows a local

Fig. 1 Prototype system overview showing a remote expert worker immerse into the local worker's environment to collaborate

worker to scan, reconstruct, and share the environment with a remote expert [26]. Gauglitz et al. demonstrated providing visual annotations in a small scale 3D space made from visual tracking to help solving a remote task [13]. Furthermore, the ability to scan and reconstruct a live 3D scene [27] provides an advantage for performance and user view independency [28]. It also allows the remote expert to be able to interact with objects on the shared environment which made 3D drawing possible [29].

Adcock et al. demonstrated room scale 3D reconstruction using a depth camera and texture projection for a remote guidance system with Spatial Augmented Reality for visual annotations [12]. Furthermore, Teo et al. [14] used pre-processing software [30] to reconstruct a static 3D environment with multiple 2D images for an object selection task in a remote collaboration. Unlike live 3D reconstruction [26], this technique relies on a live video inset rendered in front of the virtual avatar of the local worker that shows updates in the scene.

This set of prior research shows that 3D reconstruction can be achieved in many different ways. It can be expensive to host a live 3D reconstruction for a task which might only need a broad level of contextual understanding about the environment. Similarly, it is also challenging to replicate a high-quality 3D reconstruction updated in real-time.

Although switching between live 360 video sharing and live 3D reconstruction [14] provides a straight-forward solution for synchronous remote collaboration, it can be frustrating for remote workers to keep switching between the two when working with different task requirements. In order to accommodate those scenarios, we propose a hybrid system that enables the remote expert to easily toggle between live 360 video and a static 3D reconstruction integrated with interactive photo-bubbles, based on task strategies. We especially propose a novel method of using projective texture mapping of 360 images onto 3D reconstructed geometry in addition to integrating 360 images as photo-bubbles from a prior work [15] that has revealed some potential benefits.

3 System overview

Figure 1 shows an overview of our prototype system. A remote expert wears an VR Head Mounted Display (HMD) to immerse themselves into the local worker's space either in a 360 live video, or a static 3D scene. The live video was shared using a 360 camera attached to the local worker's HMD and the 3D scene was reconstructed beforehand. There are also photo-bubbles placed in the static 3D scene to further support accessibility to the finer details of the shared environment. The remote expert could use the VR controller to interact with the photo-bubble, display visual cues and toggle between the live 360 scene and 3D scene, while the local worker can see the visual cues in an AR HMD.

3.1 Live 360 video sharing remote collaboration

To prioritize on simplicity, we modeled our prototype based on SharedSphere [11] to allow for simple live 360 video sharing. In general, a local worker wears an AR HMD that shares a live 360 video stream to the remote expert. While expecting the local worker could move his/her head freely, the system counter-rotates the 360 video over the time using the rotation data from the AR HMD to stabilize the 360 video. This provides stabilization to the 360 video, reducing the motion sickness as well as providing an independent view control for the remote expert.

3.2 Collaboration in a static 3D scene

We used a static 3D reconstructed scene that was made from the Microsoft HoloLens [31] built-in mesh generator. As it would only generate an untextured room model, we then further textured it with a 360 panorama image or a video using a live projective texture mapping [32] technique implemented as a graphics shader. As a result, it provides a 3D environment where the remote expert could navigate independently, as well as to provide a high-level contextual understanding of the local worker's environment.

3.3 Visual cues for collaborations

The prototype exchanges user position and rotation data between the AR HMD of the local worker and the VR HMD and VR controllers of the remote expert in order to support nonverbal communication. The remote expert can use a visual pointer by clicking and holding on a button of a VR controller. The prototype system uses the position and orientation data of the VR controller to visualize the visual pointer on the local worker's side in AR.

While the remote user is navigating inside the 3D scene, a virtual avatar represented as a user's head is rendered to allow both users to understand each other's spatial position. In addition, a rectangle frame serving as a view awareness cue is used to provide indication for both user's viewing perspective. When a user looks away from the view awareness cues, it creates an arrow that points towards the cues to help relocating user view position. Finally when the remote user is watching shared live 360 video, the virtual avatar would disappear as the remote expert's point of view now follows the local worker. However, the view awareness cues will remain to provide understanding of the partner's view direction. Similar to the visual pointer, these were all maintained by exchanging the position and orientation data between the AR HMD and VR HMD.

3.4 Interactive 360 panoramas

The prototype features photo-bubble "360 Panos" made with 360 panorama images that are embedded in the 3D scene. As a static 3D scene can only provide a limited accessibility to the scene content, thus, we created 360 Pano to overcome the limitation. The 360 Pano allows a remote expert user to view a vantage point from the 3D scene either by viewing it as an immersive 360 image, or by choosing to use a 360 panorama image as a texture of the 3D scene. To make one, the remote expert needs to load the 360 panorama images into the prototype as a 3D sphere object using the image as the texture material. Then, the remote expert needs to manually adjust the 360 Pano's position and rotation on the 3D scene according to the vantage point. This allows the system to load the 3D scene with 360 Pano embedded.

When the system starts, the remote expert can point at a 360 Pano using the VR controller to interact with it at any time. This triggers a visual effect around the 360 Pano indicating the selection. While pointing, the remote expert can press on a button to activate the 360 Pano view. Depending on the mode setting when booting the system, this would either retexture the 3D scene or immerse the user into a 360 panorama image as shown in Fig. 1.

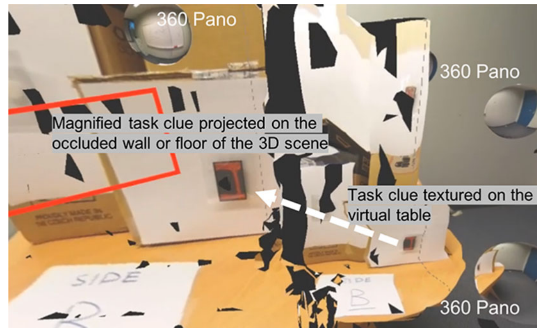

Fig. 2 Magnified texture mapped behind occluded corner

3.4.1 360 Panoramas by 360 projection

With the 360 projection mode (360proj), the prototype used a projective texture mapping technique to overwrite the texture of the current 3D scene using the 360 panorama image of the selected 360 Pano. This triggers a fade out animation as a visual feedback. In this mode, the remote expert can roam freely through the 3D scene textured with the selected 360 Pano. However, since a 360 panorama image is taken from a single point in the 3D scene, it may not be able to provide texture in every corner of the 3D scene due to possible object occlusions. As an artefact, objects behind other objects will be textured with the object in front, appearing as if the texture is magnified (see Fig. 2). Even when a 360 Pano image is projected onto the 3D scene, all of the 360 Pano images remained in the 3D scene accessible to the remote user. The remote expert could also exit to the original texture or switch to a different 360 Pano in the 3D scene at any time.

3.4.2 360 Panoramas by 360 image

In the 360 image mode (360img), the prototype enlarges the 360 Pano while hiding all of the other 360 Pano and the 3D scene. This allows the remote expert to view the 360 Pano as an immersive 360 image. Similar to the 360 projection mode, it also triggers a fade out animation as a visual feedback. In addition, the prototype moves the remote expert's virtual head position to the origin of the 360 Pano position since the remote expert is now accessing from the point of view of the 360 Pano. This also allows the remote expert to communicate with the local worker with the use of the updated position for spatial awareness and understanding.

Combined together, the prototype allows a remote expert to collaborate remotely, as well as to visit past scenes in both 360 and 3D environments.

3.5 Prototype implementation

The prototype was built using the Unity (v2017.3.1f4) game engine running on Microsoft Windows 10 PC (Intel Core i7-

6700 CPU, 3.40 GHz, 16 GB DDR4 RAM, NVIDIA GeForce 950 GPU). The remote expert used the HTC Vive HMD with 1080×1200 pixel resolution per eye with a refresh rate of 90 Hz and 110° field of view (FOV). The Vive controllers were used for controlling visual pointer, while the view awareness cues and the virtual avatar coordinates were tracked by the Vive lighthouse system. The local worker used a Microsoft HoloLens running a Unity application to connect with the remote expert via Wi-Fi connection. A Ricoh Theta V camera was attached to the HoloLens and used for sharing the live 360 video and capturing 360 panorama images. While the prototype is capable of streaming 360 video over wireless communication, for the user study, the video streaming was shared through a 10 meter high speed USB 3.0 connection to prevent network interruption with better image quality.

4 User study

We conducted a user study to evaluate our technique against the existing challenges and limitations from the prior work [15] as mentioned. We outlined our objectives of the user study through a series of research questions as follows:

1. Can different view modes alter the local worker and remote expert worker behaviour for communication, or interaction in the shared environment?
2. Does one view mode overwhelm the other in an object moving task, in terms of task performance, perceived presence, mental load, and preference?
3. Are there any indications on the succession of simplifying the system could lead to a better system performance and user experience?

The first question focused on exploring at effects of using different MR remote collaboration systems by the remote collaborators while the second question verifies the pros and cons of the two view modes. The last question tries to investigate whether our system can resolve some of the limitations highlighted by related work on a similar task. Together, we designed a user study comparing the 360 image mode against the 360 projection mode using the prototype for solving an object picking and placing task. We discuss our user study design and the measurements in the following sections.

4.1 Task configuration and conditions

The task was designed for the remote expert to provide instructions to a local worker in order to pick correct objects from the task space and place them to a specific location. For example, resembling a case of recovering a crime scene by placing objects back to its original position, or finding and placing correct pieces of an equipment in a factory. To provide instructions, the remote expert needs to access 360 Panos in order to view task clues that show where to place each object. A Japanese "Hanafuda" card set was used for the task object as it consists of different artwork that can be easily sorted into four unique sets for the four task conditions. In addition, Hanafuda cards do not consist of plain text or numbers hence cannot be easily verbally described, further encouraging nonverbal communication.

To set up, 28 pieces Hanafuda cards were divided into four sets "Set 1, Set 2, Set 3, Set 4" based on the theme of the pictures on the cards. Each set of cards was randomly distributed around the task space (a room) and captured using a 360 camera creating task clues in a form of panoramic images. Then, the 360 panorama images were converted into 360 Panos that are embedded in the 3D scene. At the beginning of each condition, two sets of cards (one set used in the task and another set to add distraction) were placed on a table in a random order and participants were allowed to pick only one card at a time and place it correctly in the room according to the clues given in 360 panorama images to the remote expert. This was to prevent the local worker from guessing the next card to pick or moving multiple cards at a time. In addition, for a user training session, 14 pieces of extra cards were prepared alongside with seven task clues provided on a mobile tablet for simulating a task in a collocated collaboration configuration.

The experiment consisted of two sessions with participants swapping roles after each session. There were two conditions in each session: 360img and 360proj. Participants in remote expert role (remote participants) had to view the task clues through 360 image mode in the 360img condition or 360 projection mode in the 360proj condition to provide instructions to the participants in the local worker role (local participants). The order of the task conditions was counterbalanced. Similarly, the order of the task objects (cards) to each condition were systematically assigned to avoid the same set of task objects being used in the same condition, and prevent participants from guessing the object to move.

4.2 User study environment and procedure

The experiment was conducted in two rooms, one for each role. Both rooms were 6m x 8m and the local worker's room had furniture around the room and a table in the middle of the room with multiple boxes stacked together on the table to simulate a task space with object occlusion. Small plastic bags were attached in various places in the local worker's room to indicate potential places where the cards can be placed. On the next door was the remote expert's room which was mostly empty for using the VR HMD. Both rooms had a table and a chair, and a computer at a corner of the room for answering questionnaires. The 10 m cable for live 360 video sharing were channeled through the ceiling in order

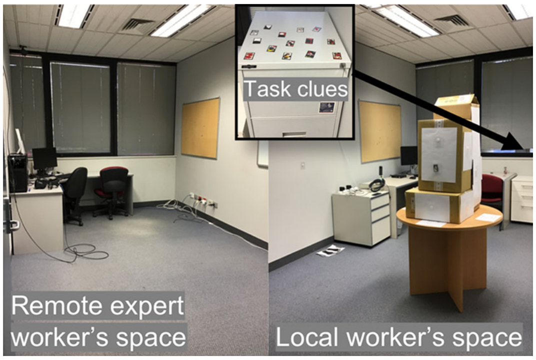

Fig. 3 Task rooms with task objects

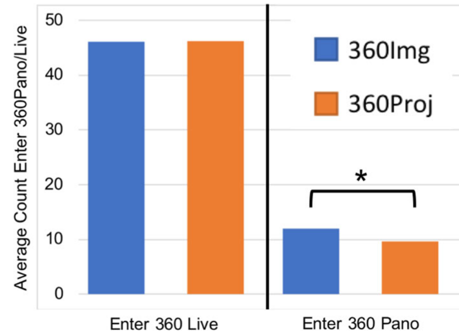

Fig. 4 Average count of entering 360 live or 360 pano to access task clues (*: significant difference)

to connect the 360 camera with the computer on the remote expert side (see Fig. 3).

Participants were recruited in pairs and assigned to a role. In the beginning of a user study session, both participants were given an information sheet, a consent form to sign and a briefing for the user study. Then, both participants were brought to the local worker's room where the task space is for a training session where they performed a practice task in a face to face collaboration. After that, participants were asked to complete a demographic questionnaire, followed by a 5 min of training of the prototype system features and task conditions to both of the participants until he or she became familiar with the interface and features. The task was completed as soon as all seven task objects were correctly placed under the guidance of the remote expert.

Following each trial, participants were asked to complete a per-condition questionnaire. Then, a second condition for the following session were carried out with another short user training at the beginning. After the task for the second condition was completed, participants were asked to answer both per-condition and per-session questionnaire. Next, participants' roles were swapped for another session, and the procedure was repeated from the user training of the first condition. Finally, participants were interviewed for comments and feedback for the prototype. Overall, the experiment took 90 min on average for each pair.

4.3 Measurements

Various measurements were used to evaluate the prototype and the conditions. User performance as objective measurement was evaluated using task completion time collected from a screen recording. For each condition, there were subjective feedback collected including Simulator Sickness Questionnaire [33], Network Mind Measure of Social Presence Questionnaire [34], MEC Spatial Presence Questionnaire [35], Single Ease Question [36], Subjective Mental Effort Question [37], and System Usability Scale [38] to measure user satisfaction and system usability. At the end of each session, a custom developed questionnaire asked user preferences between the conditions under various categories, and also qualitative feedback on reasons for their preference and possible improvements to the prototype.

5 Results

We recruited a total of 22 participants (17 male, 5 female) in pairs for the study with their age ranging from 18 to 40 years old. More than half of the participants ($N = 14$) reported some VR experience as they stated they used VR a few times a year. There were also 10 participants reported some AR experience using AR systems a few times a year. The results were statistically analyzed (alpha = .05 unless noted otherwise) and reported in this section alongside with qualitative feedback.

5.1 Objective measurements

5.1.1 Task completion time

Participants took slightly longer time in 360img ($M = 533.19$ s, $SD = 251.86$) compared to 360proj ($M = 515.50$, $SD = 212.88$). However, no significant difference was found from a paired t-test ($t(21) = 0.363$, $p = .720$).

5.1.2 Number of times participants accessed 360 panos

We recorded the number of times the remote expert participants switching into live 360 video sharing to study participants behavior on interacting with the prototype. On average, participants had a similar frequency of entering 360 live in both 360img ($M = 46.15$, $SD = 27.05$) and 360proj ($M = 46.23$, $SD = 21.80$), but the number of times they revisited the 360 Pano was significantly less in the 360proj ($M = 9.62$, $SD = 3.16$) condition than in the 360img ($M = 12.00$, $SD = 4.80$) condition as tested in a paired t-test ($t(23) = 2.403$, $p = .024$). (see Fig. 4).

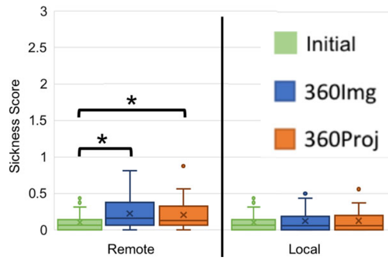

Fig. 5 Average simulator sickness score in different stages of the experiment (*: significant difference)

5.2 Subjective measurements

5.2.1 Simulator sickness

Figure 5 illustrates the average simulator sickness score of the participants at the beginning of the experiment (initial), post 360img condition (360img) and post 360-proj condition (360proj). A Simulator Sickness Questionnaire [33] including rating items on fourteen symptoms were used to survey participants' status in a scale of (0:none-3:severe). Overall, the remote expert participants experienced mild sickness (lower than one) in all stages although they spent an average of longer than 8 min in VR for each task. While significant differences were found between initial & 360img condition ($Z = -2.606$, $p = .009$) and initial & 360proj condition ($Z = -2.600$, $p = .009$) on Wilcoxon Signed Rank tests with Bonferroni correction ($\alpha = .0167$), but no significant difference between the conditions. The highest average score for "360proj" does not induce a high sickness experience that is exceeding mild level of sickness (M = 0.20, SD = 0.22). Regarding the local workers, they were using AR display hence they did not experience any significant simulator sickness.

5.2.2 System usability

System Usability Scale questionnaires [38] were collected to evaluate the usability of the prototype integrated with different 360 Pano configuration. On average, remote experts gave higher score for 360img (M = 77.21, SD = 14.42) over 360proj (M = 76.44, SD = 15.48) while the trend was in opposite for local workers (360img: M = 77.88, SD = 12.22; 360proj: M = 78.17, SD = 13.43). The average SUS scores for both roles and conditions were above 68 (or equivalent to "Good") although no significant difference was found using Wilcoxon Signed Rank tests.

5.2.3 Social presence

Social presence was measured with a questionnaire [34] which consists of eighteen rating items based on a 7-point Likert scale of (1: Fully Disagree-7: Fully Agree). A similar evaluation was carried to compare between conditions and role using two-way repeated measures ANOVA with Aligned Rank Transform [39]. Yet, there was no significant effects reported on the condition ($F(1,21) = 2.096$, $p = .153$), user role ($F(1,21) = 2.672$, $p = .107$), or interaction between them ($F(1,21) = 1.180$ $p = .281$). However, we found a high average social presence score for all participants in both conditions for both remote (360img: M = 6.08, SD = 0.67; 360proj: M = 6.13, SD = 0.80) and local (360img: M = 5.87, SD = 0.75; 360proj: M = 5.97, SD = 0.98) roles. This suggested significant results when tested against the medium score (S = 4) on both remote (360img: $Z = -4.376$, $p < .001$; 360proj: $Z = -4.347$, $p < .001$) and local (360img: $Z = -4.383$, $p < .001$; 360proj: $Z = -4.293$, $p < .001$) roles using Wilcoxon Signed Rank tests which indicates high level of social presence. While breaking into subscales, a similar result was reported where no significant result was found when comparing between the conditions or role but for comparing to the medium score.

5.2.4 Spatial presence

Participants' perceived spatial presence were measured using MEC-SPQ [35] which consists of eight rating items based on a 5-point Likert scale of (1: Fully Disagree-5: Fully Agree). In general, participants felt a strong sense of spatial presence as the average score was high for both conditions in both remote (360img: M = 4.19, SD = 0.56; 360proj: M = 4.35, SD = 0.44) and local (360img: M = 4.08, SD = 0.70; 360proj: M = 4.15, SD = 0.80) participants. According to a two-way repeated measures ANOVA with Aligned Rank Transform [39], no significant effect was reported on the conditions $F(1,21) = 1.701$, $p = .197$), the user role ($F(1,21) = .011$, $p = .917$), or interaction between them ($F(1,21) = .154$, $p = .700$). However, when tested against the medium score (S = 3.0) using a Wilcoxon Signed Rank test, significant difference was found in both conditions for both remote (360img: $Z = -3.836$, $p < .001$; 360proj: $Z = -3.918$, $p < .001$) and local (360img: $Z = -3.935$, $p < .001$; 360proj: $Z = -3.98$, $p < .001$) roles, indicating participants perceived spatial presence being higher than average level. A further analysis was tested by breaking the scale into subscales, yet, no significant difference was found between the conditions. Similar to social presence results, all subscales reported significant result when tested against the medium score.

5.2.5 Mental effort

Participants' perceived mental effort were measured by a questionnaire [37] which consists of a single scale from 0 to 150 with nine labels from "Not at all hard to do" to

"Exceeding tremendously hard to do". On average, participants felt the tasks were between "Not very hard to do" and "A bit hard to do". Remote participants felt 360proj (M = 18.65, SD = 12.85) is slightly easier than 360img (M = 18.96, SD = 20.38) in average while local participants had an opposite thought (360img: M = 13.15, SD = 15.61; 360proj: M = 13.65, SD = 16.78). Using two-way repeated measures ANOVA with Aligned Rank Transform [39], a significant effect of the user role (F(1,21) = 19.519, $p < .001$) was found in the results which suggests remote participants felt the task was harder than the local participants. However, no significant effect was found in the condition (F(1,21) = .420, $p = .520$) or interaction between the role and the condition (F(1,21) = .058, $p = .810$).

5.2.6 User experience

Participants' user experience was evaluated using SEQ [36] and three custom rating questions Q1: "I enjoy the experience", Q2: "I was able to focus on the task activity", and Q3: "I understood where my partner's focus was on" using 7-point Likert scale (1: Strongly Disagree-7: Strongly Agree). Overall, participants' ratings were mostly positive as they gave no less than 5.46 out of 7 for both condition and role. In SEQ, local participants had (360img: M = 6.18, SD = 1.10; 360proj: M = 6.36, SD = .79) and remote participants had (360img: M = 5.50, SD = 1.60; 360proj: M = 5.50, SD = 1.41). In Q1, local participants had (360img: M = 6.00, SD = 1.27; 360proj: M = 6.18, SD = 1.01) and remote participants had (360img: M = 6.23, SD = 1.23; 360proj: M = 6.23, SD = 1.11). In Q2, local participants had (360img: M = 6.50, SD = 0.74; 360proj: M = 6.55, SD = 0.67) and remote participants had (360img: M = 6.18, SD = 1.47; 360proj: M = 6.23, SD = 0.92). In Q3, local participants had (360img: M = 5.50, SD = 1.71; 360proj: M = 6.14, SD = 1.08) and remote participants had (360img: M = 6.59, SD = 0.67; 360proj: M = 6.36, SD = 1.22). There were also significant effect reported using two-way repeated measures ANOVA with Aligned Rank Transform [39] in the user role on both the SEQ (F(1,21)= 10.611, $p = .002$) and Understanding the partner's focus (F(1,21) = 8.594, $p = .005$).

Qualitative feedback indicated the local participants felt that it was harder to follow their partner in 360img as they mentioned (P3, M, Late 10s, VR/AR inexperience) "I was confused with my partner's location from the headset vision, his head would sometimes disappear" and (P20, M, Mid 20s, VR/AR expert) "sometimes the partner seemed separated from me while looking for the next task". However for 360proj, participants felt it was easier to follow or trace the remote participant's position as one mentioned (P3) "Was easy to see where the remote user was looking at just by following the 3D head even before my partner had to give me instructions". On the opposite side, remote participants felt 360img gives clearer perspective at point of interest as one commented (P4, M, Mid 20s, VR/AR inexperience) "the 360 image made object look clearer hence made it even more easier".

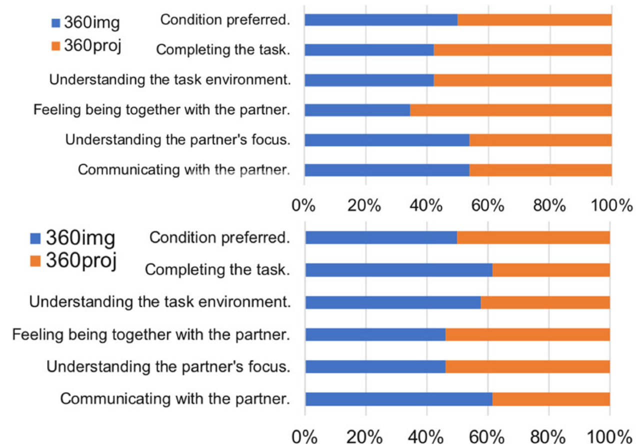

Fig. 6 Participants preferences based on remote (top) and local role (bottom)

5.2.7 User preferences

Participants' preferences were collected in each role using custom questions as summarized in Fig. 6. Participants were nearly split into half when asked to decide for a preferred condition. However, remote participants were leaning more towards 360proj for solving tasks and understanding the task environment while it became the opposite case in the local role.

When asked for the reason for choosing the option in the remote role, participants who gave credit to 360img liked the ease of quick traveling. A few participants commented (P7) "the ease and speed of 'moving' through the environment... seemed to lower the cognitive load for me.", (P19, F, Early 30s, VR/AR novice) "Feel like I don't have to worry too much about occlusion when physically moving around". Participants also felt 360img had a better image clarity as one mentioned (P4) "the images were clear compared to the 360proj". On the opposite, participants mentioned 360proj provides better navigation control, spatial understanding and simplicity as a few mentioned (P18, M, Late 10s, VR novice) "It was a lot easier to understand my surroundings with the projection", (P23, F, Late 10s, VR novice) "...it will be easier to imagine the real thing and their sizes" and (P10, M, Early 30s, VR/AR expert) "... I only had to jump between two views and not three which made things a lot simpler". A few participants also seemed took advantage of the magnified texture artefact stating (P5, M, Late 10s, VR/AR inexperience) "... the bigger pictures gave much more clarity" and (P20) "In some cases when the card was small the larger projection behind it helped to see detail".

Although the interface was focused more on the remote role, local participants could still distinguish a slight variant between the features as well. Participants preferred 360img mainly because of the task were completed quicker as they commented (P6, M, Late 10s, AR novice) "partner seemed to have a better understanding of where stuff was", (P7, M, Early 30s, VR/AR proficient) "... the task was completed with less delay and faster". Participants also felt their partner were with them more in 360proj mentioning (P13, F, Late 10s, VR/AR inexperience) "It was much easier to follow the movements of my partner around...", (P20) "It felt like my partner was with me more...", (P27, M, Mid 20s, VR/AR proficient) "I felt like I saw my partner more".

5.3 Suggested improvements

When asked for suggestions, a group of local participants (N = 5) commonly agreed towards a lighter headset with wider field of view. There were also some participants (N = 6) suggesting for improved ability to see their partner's action as one mentioned (P7) "granting the local user the ability to have a better understanding of the remote user's actions...". Lastly, few participants (N = 4) also suggested for improved visual pointer accuracy.

When discussed upon the remote side, three participants mentioned a need for an improved 3D reconstruction as they said (P7) "... Maybe improving the image quality in the two modes could also improve the experience", (P20) "Higher resolution scan of the room with higher resolution textures for the cards", (P25, F, Early 30s, VR/AR inexperience) "better resolution and less gaps in the environment". One participant also suggested for ability to use both 360img and 360proj at the same time, saying (P7) "I think the freedom to use either a 360img or a 360proj in a freeform mode could greatly improve the system, as this would make it easier to switch work modes in the middle of a task". Another participant also suggested 360 live video sharing could be improved, saying (P27) "make it so the remote expert doesn't have to rotate their head to see where local worker is looking... so (when) the system switch to live view always looks where the local worker is looking". A participant also suggested for improving task clue image quality in 360proj as s/he said (P23) "it would be great if the image in the 360proj can be as clear as the one in 360img". Although 360img and 360proj were using the same image resource, the 360proj may have appeared stretched as it is mapped onto the 3D geometry.

6 Discussion

Overall, the prototype showed a sample usage of the hybrid remote collaboration system for a remote expert collaboration task. In the experiment, the 360 Pano was used for enabling a remote participant to be an expert in the experimental task as it provides information to the task solution. However, it can also be used for an equal role collaboration task where a remote worker could use the 360 Pano to access information that can be shared with a local worker. Yet, in terms of the findings, it was suggested that the prototype can provide a high collaborative experience for an MR remote collaboration. This includes higher sense of social presence, spatial presence, user experience and lower cognitive load. Although some of the features were not assessed individually, we note that the prototype featuring live 360 video sharing and 3D scene reconstruction can potentially promote task performance or provide variation in task solving as suggested in a few related investigations [13,14,24,28,40]. In addition, having multiple visual cues such as visual pointer, virtual avatar and view awareness cues may also be the underlying factor that increases the social presence, spatial presence, and provide low mental effort in a remote collaboration [9,16,24,25,41].

Based on the observation from the user study, local participants would initially seek for the ease of noticing their partner's visual cues in the early stage, but later they became less aware of it as long as they could listen to their partner's verbal instruction clearly and only seek for visual cues when it is necessary. This was similar to both modes although local participants tried to follow remote participants longer in 360proj. Aligning this with the subjective feedback, this may be either the hardware limitation or the effect of 360img that caused the remote expert to be able to quickly travel across different vantage points hence making the avatar jump from on place to another resulting in participants giving up on searching for the nonverbal communication. Although this was not part of the analysis, it could have indirectly affected the result. In other words, the results could be different if the AR HMD were replaced with a wider FOV or with an improved user awareness for the remote expert's virtual avatar. It was also suspected that the design of the task might have brought some impacts to the results. For example, local participants who were better at placing cards into sleeves could take less time for the execution and thus have a shorter task completion time. However, this should only had minor effect due to the use of within-subject design.

In terms of remote user role, participants were struggling to see the task objects clearly using the live 360 video. We found that the choice of a 360 camera and the height difference between the participants may have caused the issue as the 360 camera was attached on the local participant's head. Although participant's height is an uncontrolled variable, the task performance may be better if the local participants is shorter than the remote participants or if a 360 camera with a better resolution was used. However, none of the participants made errors in picking or placing the task objects hence it was postulated that the effect of height difference could be minor to this particular task. While seeing from a different height angle or prolonged experiment duration in VR/AR can be visually uncomfortable, participants gave a relatively low score on simulator sickness. Compared to an investigation using a similar prototype configuration but without 360 Pano [14], it is suspected that using fade-in/out as a transition effect could have eased the simulator sickness [42].

6.1 360img: pros and cons

According to the subjective rating scores, the results did not reveal any significant difference between the conditions, but both conditions showed high average scores in several aspects. However, participants' qualitative feedback suggested benefits and drawbacks that are distinct between the two.

In 360img, remote participants could see the task clue represented in a large 360 panorama image without getting close to vantage positions after activating the 360 Pano. We predicted this should provide a lower task completion time, however, participants actually took longer time in 360img and had a higher revisiting count on the task clues. Based on our observation, we suspect that the ease of viewing the task clue without walking close to the vantage point could cause the participant become disoriented and get confused between completed and uncompleted task clues hence revisiting more. In addition, local participants also felt harder to follow their partner in this condition as the remote user's avatar constantly jumped from one position to another. On the positive side, 360img provides a clearer vision as it renders the view as an image without a mesh or depth details thus some participants had an impression that the resolution was higher, although the images were in the same resolution as in 360proj.

6.2 360proj: pros and cons

With 360proj, the remote participants needed to get close to vantage positions in order to see the task clue. This forced the remote participants to navigate more inside the 3D scene hence increasing the task completion time. However due to this, remote participants were able to track their progression better towards the completed task clues as it provides a better spatial understanding not only of the vantage point of a task clue, but also of its surroundings.

In parallel, this also made local participants easier to follow with the remote participants and hence sometimes they were able to predict their partner's movement. However, the task clues were projection mapped to the 3D scene, so if the task clue is physically unreachable or in an awkward angle, it would become challenging to access them. This aspect has only been lightly considered in the study by having a few task clues in lower spot, but it may have only given advantage to participants with shorter height. In other words, taller participants ($h > 170$ cm) did not find it particularly harder as they only needed to bend down in order to reach those task clues.

6.3 360img versus 360proj: strategy and differentiation

In general, 360img and 360proj had its own benefits and drawbacks. The findings also show that neither of the view mode is dominating the other in terms of usability and performance in a object moving task. In the user study where we evaluated participants' behaviour using an object picking and placing task, we found that 360img is optimal for tasks where understanding surroundings is less important and room structure is awkward for physical interaction, while 360proj can be better for tasks where object size estimation or spatial understanding are important. For a quick-use purpose, 360proj had less interface hence making the learning process quicker although having more view modes can give more option to the control the way to access information.

This reflects on their strategy as remote participants in the 360img condition where they did not try to remember which 360 Pano they visited, but rather recognize the content "360 panorama image" in the 360 Pano. In their task solving strategy, they began by selecting the reachable 360 Pano and started giving instructions to the local participant. Once all of the 360 Panos were completed within the area, they would go through the room in circle until they encounter a 360 Pano, regardless of if it was previously visited. Then, they would select the 360 Pano and try to recognize whether if the given task clue was completed. Finally, they repeated the steps until they finished every task clues as notified by the instructor. However, if there was a task clue that they missed, they would revisit all 360 Panos in the same pattern again until they found the missing task clue.

In the opposite, remote participants in the 360proj condition would try to recognize and differentiate between visited and unvisited 360 Pano without seeing the content. As we observed, most of the participants would begin by selecting their nearest 360 Pano and start giving instructions to the local participant. Once completed, they would walk back to their previous position and search for the next unvisited 360 Pano, then, repeat by walking in the room in circle. For the case when they missed a 360 Pano, they would try to recall by recognizing the 360 Pano instead of repeating the procedure like they did with the 360img. As a result, it shows that in 360proj participants entered 360 Pano significantly less frequently than in the 360img as shown on Fig. 4.

In addition to the user behaviour, we did not notice a change in the task solving strategy when participants' role were swapped. However, in our observation, we found that participants in the second session became more confident in giving instructions to their partner using nonverbal communication. In other words, both remote and local participants had doubts on using their visual cues in the first session because they could not tell whether their visual cues are showing correctly on their partner's interface despite the visual feedback on their respective view. This is especially when the local participants thought the constant switching of the visual cues in 360img was an error and therefore, ignored the nonverbal communication. As a result, this led some remote participants to think that the visual cues were not working correctly. However, this ambiguity was resolved immediately after participants switched their role in the second session. Overall, we did not find any significant difference in terms of task completion time after a post hoc analysis on their performance based on their sessions.

Mixing the 360img and 360proj while trying to balance between the system complexity and usability is yet another challenge to overcome. In our design, We enforced the system simplicity by restricting remote participants from being able to switch freely between 360img and 360proj. Furthermore, we wanted to evaluate whether one view mode overwhelms the other as stated in our research question in Sect. 4. This was not only to simply observe and compare results of the two, but also to connect the first and third research question. In other words, it helps identifying any common attributes between the two and to determine whether it is essential to mix them together while preserving its simplicity. The results show that the system in either condition has a "good" usability but it is still insufficient to justify the result. Yet, it does not mean mixing the two could lead to a bad usability as we suspect having more options would certainly give variation in solving different types of task in a MR remote collaboration [14].

6.4 Limitations

Although our user study investigated an MR remote collaboration using an object picking and placing task in a space with occlusions, there were still limitations. First, the user study was conducted in a lab space and in a controlled environment with participants recruited from around the campus. This restricts the type of participants and the room configuration that was different from a typical work space that the system was intended for. For example, having objects at a high place or complex room structure. Studying in an actual use case and workspace could help reveal any potential benefits or issue with using the system in the real-world context.

Second, the quality of the 3D reconstruction was not good due to the hardware limitation of the HoloLens. As seen in Figs. 1 and 2, the noticeable amounts of holes on the 3D scene may have limited user's capability and perception of some details in the scene. Although this was partly due to aiming for simplicity in terms of system configuration in this project, we suspect that the results could be different if a perfectly reconstructed 3D scene was used. Furthermore, using a static 3D scene may constraint upon tasks requiring dynamic environment. For example, a remote collaboration task that involves furnishing a room needs a live 3D reconstruction in order to provide synchronous collaboration and discussion.

Some hardware used for the prototype also had limitations. For example, narrow FOV or heavy weight of the AR HMD on the local participant spoiled the user experience. Limited resolution of the 360 camera could have also contributed towards weakening the user experience. Software wise, a better tracking algorithm is needed for visual pointer to work correctly as the enlarged 360 panorama image in 360img caused the view for the remote expert become stretched out, hence causing an offset when the remote participants were trying to use visual pointer when inside the 360img.

7 Conclusion and future work

In this paper we presented an interactive hybrid MR remote collaboration system combining live 360 video sharing and 3D reconstructed scene embedded with photo-bubble that allows the remote expert to collaborate with the local worker with variations. The prototype allowed the remote expert to interact with photo-bubble known as 360 Pano that can be viewed as an immersive 360 image "360img" or viewed as a texture of the 3D reconstructed environment using projective texture mapping technique "360proj".

A user study was conducted using object moving tasks in a room-scale space. We fragmented our goals into three research questions (RQs). Regarding RQ1:"Can different view modes alter the local worker and remote expert worker behaviour for communication, or interaction in the shared environment?", we found that using a different view mode can change the way a remote expert worker interacts with the system, and passively affect the local worker. The remote expert worker took the advantage of "quick travel" in the 360img in order to switch between the 360 Panos, however, in the 360proj the remote expert needed to walk in the 3D environment in order to observe the task clues. This severely affected the remote collaboration in terms of communication patterns relying on 3D avatar, remembering the task versus recognizing the content, and spatial understanding of the shared environment.

In terms of RQ2: "Does one view mode overwhelm the other in an object moving task?", the results indicated a tie between the 360img and 360proj. First, a higher than average score was found in all aspects of perceived social presence and spatial presence for both modes. Although there was no clear winning condition in terms of task performance, perceived presence, and mental load, the findings suggested both modes had its own benefits and limitations based on qualitative feedback. Using 360img provided a better clarity for a vantage point and it required less physical movement. However it did not offer good spatial understanding of the surroundings. On the other hand, 360proj was useful for accessing a vantage point where understanding size or depth information becomes essential. However, the user needed to walk to the vantage point to see the information. While the proposed use case was focused on a remote expert collaboration, the prototype system also suggested potential capabilities at equal role collaboration.

Finally, for RQ3:"Are there any indications on the succession of simplifying the system could lead to a better system performance and user experience?", we observed a "good" usability level and positive subjective feedback that provided insights and indications. For example, a hybrid system was found being easier for the local workers to follow and understand instructions, while for the remote expert workers it required a lower physical and mental effort to navigate in the shared environment and to provide instructions.

In the future, we will consider experimenting the prototype system with different configurations in order to evaluate different use cases. We will also try to enhance the system by combining the two modes into a single configuration to allow for variation in task solving. In addition, we plan to replace the head-only virtual avatar with a human-size full-body virtual avatar and also improve the visual pointer algorithm so that overall performance could be improved. Second, we would like to replace the local worker's AR headset with one that is lighter and has a larger field of view and also with a better 3D scanner with simple configuration to improve user experience. Finally, we also plan to redesign the task and room configuration set-up for a better evaluation of the prototype from different aspects.

Together with this, we expect our work will contribute towards a new telecommunication system where it allows a remote expert to access the local worker's space in a more interactive way, which would also lead to extending the capabilities of the current MR remote collaboration system.

References

1. Adcock M, Feng D, Thomas B (2013) Visualization of off-surface 3D viewpoint locations in spatial augmented reality. https://doi.org/10.1145/2491367.2491378
2. Palmer D, Adcock M, Smith J, Hutchins M, Gunn C, Stevenson D, Taylor K (2007) Proceedings of the 2007 conference of the computer-human interaction special interest group (CHISIG) of Australia on Computer–human interaction: design: activities, artifacts and environments—OZCHI '07. ACM Press, New York, p 103. https://doi.org/10.1145/1324892.1324911. http://portal.acm.org/citation.cfm?doid=1324892.1324911
3. Orts-Escolano S, Rhemann C, Fanello S, Chang W, Kowdle A, Degtyarev Y, Kim D, Davidson PL, Khamis S, Dou M, Tankovich V, Loop C, Cai Q, Chou PA, Mennicken S, Valentin J, Pradeep V, Wang S, Kang SB, Kohli P, Lutchyn Y, Keskin C, Izadi S (2016) Holoportation: virtual 3D teleportation in real-time. https://doi.org/10.1145/2984511.2984517
4. Pejsa T, Kantor J, Benko H, Ofek E, Wilson AD (2016) Room2Room: enabling life-size telepresence in a projected augmented reality environment. https://doi.org/10.1145/2818048.2819965
5. Piumsomboon T, Lee GA, Hart JD, Ens B, Lindeman RW, Thomas BH, Billinghurst M (2018) Mini-Me. https://doi.org/10.1145/3173574.3173620
6. Le Chenechal M, Chalme S, Duval T, Royan J, Gouranton V, Arnaldi B (2015) International conference on collaboration technologies and systems (CTS). IEEE, pp 233–240. https://doi.org/10.1109/CTS.2015.7210428. http://ieeexplore.ieee.org/document/7210428/
7. Garcia-Pereira I, Gimeno J, Perez M, Portales C, Casas S (2018) IEEE international symposium on mixed and augmented reality adjunct (ISMAR-Adjunct). IEEE, pp 179–183. https://doi.org/10.1109/ISMAR-Adjunct.2018.00062. https://ieeexplore.ieee.org/document/8699172/
8. Huang W, Alem L, Tecchia F (2013) SIGGRAPH Asia 2013 emerging technologies on—SA '13. ACM Press, New York, pp 1–3. https://doi.org/10.1145/2542284.2542294. http://dl.acm.org/citation.cfm?doid=2542284.2542294
9. Teo T, Lee GA, Billinghurst M, Adcock M (2018) Proceedings of the 30th Australian conference on computer–human interaction—OzCHI '18. ACM Press, New York, pp 406–410. https://doi.org/10.1145/3292147.3292200. http://dl.acm.org/citation.cfm?doid=3292147.3292200
10. Adcock M, Ranatunga D, Smith R, Thomas BH (2014) Proceedings of the 2nd ACM symposium on spatial user interaction—SUI '14. ACM Press, New York, pp 113–122. https://doi.org/10.1145/2659766.2659768. http://dl.acm.org/citation.cfm?doid=2659766.2659768
11. Lee GA, Teo T, Kim S, Billinghurst M (2017) Sharedsphere: MR collaboration through shared live panorama. https://doi.org/10.1145/3132818.3132827
12. Adcock M, Anderson S, Thomas B (2013) RemoteFusion: real time depth camera fusion for remote collaboration on physical tasks. https://doi.org/10.1145/2534329.2534331. http://dl.acm.org/citation.cfm?doid=2534329.2534331
13. Gauglitz S, Nuernberger B, Turk M, Höllerer T (2014) Proceedings of the 20th ACM symposium on virtual reality software and technology—VRST '14, pp 197–205. https://doi.org/10.1145/2671015.2671016. http://dl.acm.org/citation.cfm?doid=2671015.2671016
14. Teo T, Lawrence L, Lee GA, Billinghurst M, Adcock M (2019) Proceedings of the 2019 CHI conference on human factors in computing systems—CHI '19. ACM Press, New York, pp 1–14. https://doi.org/10.1145/3290605.3300431. http://dl.acm.org/citation.cfm?doid=3290605.3300431
15. Teo T, Hayati AF, Lee GA, Billinghurst M, Adcock M (2019) 25th ACM symposium on virtual reality software and technology on-VRST '19. ACM Press, New York, pp 1–11. https://doi.org/10.1145/3359996.3364238. http://dl.acm.org/citation.cfm?doid=3359996.3364238
16. Piumsomboon T, Day A, Ens B, Lee Y, Lee G, Billinghurst M (2017) Exploring enhancements for remote mixed reality collaboration. https://doi.org/10.1145/3132787.3139200
17. Kasahara S, Rekimoto J (2015) Proceedings of the 21st ACM symposium on virtual reality software and technology, vol 23, no 3, p 217. https://doi.org/10.1145/2821592.2821608

18. NP. Jouppi, NP (2002) Proceedings of the 2002 ACM conference on computer supported cooperative work—CSCW '02. ACM Press, New York, p. 354. https://doi.org/10.1145/587078.587128. http://portal.acm.org/citation.cfm?doid=587078.587128
19. Yamazawa K, Onoe Y, Yokoya N, Takemura H (2000) Systems and computers in Japan, vol 31, no 6, p 56. https://doi.org/10.1002/(SICI)1520-684X(200006)31:6<56::AID-SCJ6>3.0.CO;2-0. http://doi.wiley.com/10.1002/%28SICI%291520-684X%28200006%2931%3A6%3C56%3A%3AAID-SCJ6%3E3.0.CO%3B2-0
20. Schulz R, Ward B, Roberts J (2013) ICRA 2013 workshop: human robot interaction (HRI) for assistance and industrial robots. Scientific knowledge, standards and regulatory framework. How do I design for the real world?, Karlsruhe, Germany, pp 37–38
21. Matsuda A, Miyaki T, Rekimoto J (2017) Proceedings of the 8th augmented human international conference on-AH '17. ACM Press, New York, pp 1–9. https://doi.org/10.1145/3041164.3041182. http://dl.acm.org/citation.cfm?doid=3041164.3041182
22. Tang A, Fakourfar O, Neustaedter C, Bateman S (2017) Proceedings of the 2017 conference on designing interactive systems, pp 1327–1339. https://doi.org/10.1145/3064663.3064707
23. Piumsomboon T, Lee GA, Irlitti A, Ens B, Thomas BH, Billinghurst M (2019) Proceedings of the 2019 CHI conference on human factors in computing systems—CHI '19. ACM Press, New York, pp 1–17. https://doi.org/10.1145/3290605.3300458. http://dl.acm.org/citation.cfm?doid=3290605.3300458
24. Tait M, Billinghurst M (2015) The effect of view independence in a collaborative AR system. Comput Support Coop Work (CSCW) 24(6):563. https://doi.org/10.1007/s10606-015-9231-8
25. Lee GA, Teo T, Kim S, Billinghurst M (2018) 2018 IEEE international symposium on mixed and augmented reality (ISMAR). IEEE, pp 153–164. https://doi.org/10.1109/ISMAR.2018.00051. https://ieeexplore.ieee.org/document/8613761/
26. Stotko P, Krumpen S, Hullin MB, Weinmann M, Klein R (2019) Slamcast: large-scale, real-time 3d reconstruction and streaming for immersive multi-client live telepresence. IEEE Trans Vis Comput Graph 25(5):2102. https://doi.org/10.1109/TVCG.2019.2899231
27. Dai A, Nienerbner M, Zollhofer M, Izadi S, Theobalt C (2017) Bundlefusion: real-time globally consistent 3d reconstruction using on-the-fly surface reintegration. Trans ACM Graph 36(4):1. https://doi.org/10.1145/3072959.3054739
28. Gauglitz S, Nuernberger B, Turk M, Höllerer T (2014) Proceedings of the 27th annual ACM symposium on User interface software and technology—UIST '14. ACM Press, New York, pp 449–459. https://doi.org/10.1145/2642918.2647372. http://dl.acm.org/citation.cfm?doid=2642918.2647372
29. Adcock M, Gunn C (2010) ACM SIGGRAPH ASIA. Posters on-SA '10. ACM Press, New York, p 1. https://doi.org/10.1145/1900354.1900423. http://portal.acm.org/citation.cfm?doid=1900354.1900423
30. Agisoft. PhotoScan. http://www.agisoft.com/
31. HoloLens M https://www.microsoft.com/en-us/hololen
32. Segal M, Korobkin C, van Widenfelt R, Foran J, Haeberli P (1992) Association for Computing Machinery (ACM), pp 249–252. https://doi.org/10.1145/133994.134071
33. Kennedy RS, Lane KSBNE, Lilienthal Michael G (1993) Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int J Aviat Psychol 3(3):203
34. Harms C, Biocca F (2004) Seventh annual international workshop: presence, p 246
35. Vorderer P, Gouveia FR, Biocca F, Saari T, Jäncke F, Böcking S, Schramm H, Gysbers A, Hartmann T, Klimmt C, Laarni J, Ravaja N, Sacau A, Baumgartner T, Jäncke P, Wirth W (2004) MEC spatial presence questionnaire. MEC- SPQ), short documentation and instructions for application
36. Sauro J, Dumas JS (2009) Comparison of three one-question, post-task usability questionnaires
37. Zijlstra FRH (1993) Efficiency in work behaviour: a design approach for modern tools
38. Brooke J (1996) SUS: a quick and dirty usability scale
39. Wobbrock JO, Findlater L, Gergle D, Higgins JJ (2011) Proceedings of the 2011 annual conference on Human factors in computing systems—CHI '11. ACM Press, New York, p 143. https://doi.org/10.1145/1978942.1978963. http://dl.acm.org/citation.cfm?doid=1978942.1978963
40. Gauglitz S, Lee C, Turk M, Höllerer T (2012) Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services—MobileHCI '12. ACM Press, New York, p 241. https://doi.org/10.1145/2371574.2371610. http://dl.acm.org/citation.cfm?doid=2371574.2371610
41. Günther S, Kratz S, Avrahami D, Mühlhäuser M (2018) Proceedings of the 11th PErvasive technologies related to assistive environments conference on-PETRA '18. ACM Press, New York, pp 339–344. https://doi.org/10.1145/3197768.3201568. http://dl.acm.org/citation.cfm?doid=3197768.3201568
42. Rahimi Moghadam K, Banigan C, Ragan ED (2018) Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness. IEEE Trans Vis Comput Graph. https://doi.org/10.1109/TVCG.2018.2884468