Augmented Reality Collaborative Medical Displays (ARC-MeDs) for Multi-User Surgical Planning and Intra-operative Communication

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ABSTRACT
Digital Displays are integral to modern systems and serve as the primary visual human-computer interface. A physical monitor is a typical example for showing computer-generated information to a person - as long they are located directly in front of them. In an operating room, however, people may be unable to move freely or communicate only based on verbal communication due to noise pollution. Furthermore, mobile and connected editing and sharing of the same content on the go is currently not readily available. Therefore, we propose Augmented Reality Collaborative Medical Displays for duplicating any displayed content as a virtual monitor hovering in space in the real world. Our method replicates any user input on the virtual representation onto the original physical monitor. We put forward a use case in planning a surgical intervention of the abdomen with intra-operative CT imaging. Moreover, we demonstrate how a medical immersive teleconsultation system utilizes our method for meaningful interactions. Finally, we evaluate our method with multiple display resolutions. Based on our observations from the use cases and quantitative evaluation, we believe our proposed concept facilitates the integration of future collaborative medical applications.

KEYWORDS
Multi-display System, Mixed Reality, Co-located Collaboration, Surgical Planning

1. Introduction

Digital Displays are an integral part of modern systems and are essential to human-computer interfaces. As the technology evolved, people can not only view contents from a display physically located in the same room as the user but also access the displays from a remote location. This is thanks to the features such as remote desktop accessing and online meeting screen sharing.

In an operating room (OR), endoscopic video streams or medical imaging data such as MRI or CT are often displayed simultaneously on several displays. When not standing near a mouse or the touchscreen, however, conventional display methods do not offer remote control of its content nor provide an interface for people to aid ongoing communication. In addition, depending on the person's role, they may be unable to move freely due to their duty to preserve sterility. Unfortunately, a solution for this

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Figure 1. Collaborative Exploration of CT-Images. Our system creates a personal Augmented Reality Collaborative Medical Display for each user with a head-mounted display. The remaining people without head-mounted displays within the same room can participate in the conversation through the large monitor.

both physical and metaphorical gap is not readily available. Instead, surgeons and assistants need to rely on purely verbal communication. In such cases, medical devices that add to the peripheral noise level of the OR may drown out verbal communication.

With the advancement of 3D technology for Mixed Reality (MR), methods for immersively displaying 3D information in a user's environment gain importance. For example, multiple users often desire to collaborate and share their views in a co-located environment, such as in classrooms, offices, or ORs (Bork et al. (2019); Cartucho et al. (2020); Song et al. (2022b)), with others within the room while working together on a joint task. While screen-based teleconference systems can utilize screen-sharing to share their display content with users, 3D MR devices can further expand on the concept of screen sharing. We propose the concept of Augmented Reality Collaborative Medical Display (ARC-MeD) that enables users to share the content of conventional 2D screens as a floating virtual monitor displayed through MR technology for other users, as seen in Figure 1. When the 3D pose of a physical monitor is known, any 3D interaction on the virtual monitor, such as annotations or user inputs, is reproduced at the physical monitor and vice versa.

We present two use cases in which we demonstrate our concept in a co-located environment and a telepresence environment. Further, we evaluate performance of our ARC-MeD implementation under different configurations. Based on the results, we propose recommended settings for future systems.

2. Related Works

Our concept aims to improve communication in an environment where a physical display shows essential information, but due to physical constraints (such as positioning of the display or the people themself), not everyone can see and interact with its content. ARC-MeD aims to solve this problem by enabling users to collaborate through 3D displays such as MR headsets. Like Multi-display Groupware Systemss (MDGs), every user within the system has access to personal devices, in our case, MR head-mounted displays (HMDs). Users can interact and annotate with the duplicated content of conventional screens within the environment from their personal display. In the following, we discuss the positioning of our concept in the related work.

2.1. Multi-display Groupware (MDG) Systems

MDG systems enables multiple users to work on shared screen-based tasks collaboratively. They typically comprise one or more public screens visible to all users in the collaboration space. Moreover, every user can access a private display intended just for them to interact (Liu and Kao (2007); Sugimoto et al. (2004); Wallace and Li (2007); Wigdor et al. (2009); Fender et al. (2017)). As the public display may contain the content generated by all users, typical MDG systems use large displays or projectors to create a large surface on which the system visualizes its content. Liu and Kao (2007) demonstrated that users who could observe shared content of other users on a large wall display could collaborate and communicate better compared to the scenario where users only had their personal views. Moreover, Hawkey et al. (2005) showed that users preferred to work on the same display; however, collaboration was more difficult due to users having to share the physical space in front of the display. In a setting where one or more users sat further away, they felt more comfortable and could quickly overview the entire screen; however, they could only collaborate worse than before.

Our concept visualizes individual displays through Augmented Reality (AR) and is entirely virtual. As a result, virtual monitors have the advantage of free positioning in 3D space, flexible scaling, and portability without cumbersome display devices such as a tablet.

2.2. Sharing Content in Mixed Reality

Schäfer et al. (2021) authored an extensive review on MR collaboration systems. They found that media sharing and AR annotations are one of the most used interaction types for such a system, only surpassed by shared object manipulation. However, no work has connected a virtual display as a remote control for a physical display with a combination of bi-directional user annotations. One of the earliest methods of remote visualization in MR includes the concept of World-in-Miniature (WiM) by Stoakley et al. (1995), in which parts of the virtual world are replicated within a virtual miniature that improves user interaction and perception of the surrounding virtual environment. Due to the advances in MR devices, including optical see-through (OST) displays and Virtual Reality (VR) HMDs, interaction methods for sharing 3D content have become more viable for immersive, real-time collaboration. WiMs has been adapted for teleconsultation in asymmetric telepresence using real-time environmental data for VR (Yu et al. (2021)) and later for AR for co-located collaboration (Yu et al. (2022)).

Like WiMs, similar methods utilizes a Digital Twin for remote collaboration, such as the Voodoo-dolls by Pierce et al. (1999) for arbitrary virtual objects, immersive robotic control (Havard et al. (2019)), or medical telesurgery (Laaki et al. (2019)). However, such methods are typically used for virtual objects and have not been proposed for 2D monitors within a 3D environment.

Moreover, in the context of HMD-based MR telepresence, remote users can interact with point clouds or mesh representations of a scene and share live annotation with users wearing HMDs in the local scene. Especially during the COVID-19 global pandemic, teleconsultation (Weibel et al. (2020); Gasques et al. (2021); Roth et al. (2021)) could solve the shortage of medical experts, reduce personnel traffic, and thus decrease the risk of spreading infection. In addition, prior work such as Song et al. (2022a) explores the fusion of static and dynamic sensors to improve the quality of the MR telepresence.

The requirement of these related works is access to the 3D geometry of the scene; however, they neglect fidelity and interaction of 2D monitors within the room. Qian et al. (2017) investigated virtual monitors as a replacement for physical monitors. Deib et al. (2018) and Deib et al. (2020) transferred their methods for use in medical interventions, i.e., percutaneous spine procedures and mechanical thrombectomy for stroke procedures. However, these works are not looking into a shared space's collaborative aspects of a physical and virtual monitor.

Neither MDGs, variations of WiM, nor virtual monitors have addressed the use of virtually generated displays and physical monitors simultaneously for co-located collaboration using MR. Our method combines the advantages of a shared workspace with personal user space, access to advanced MR interaction methods such as WiM, and flexibility of virtual monitors. Therefore, to the best of our knowledge, our concept is the first method to fill the gap of linking a virtual monitor with the physical monitor for remote interaction and collaboration between multiple users.

3. Method

ARC-MeD can be understood as a virtual replication of an existing conventional display. However, one fundamental difference is that we link the duplication to the original display. Therefore, interaction on either display mirrors the changes to all other duplications. Our system framework has two primary components: The streaming unit of the display content and the receivers. In particular, we connect the streaming unit to the physical monitors, which acquires the current content of the display and creates a network communication interface for streaming the content to the ARC-MeD. The receiving HMDs read and visualize the streaming data while processing user input. The Figure 3 represents the components and architecture of the system.

3.1. Digital Display Duplication

In order to identify different physical displays in the room, our system uses Pure Python QR code generator[1] to generate a unique QR code on the screen of the display, which encodes the IP address, screen size, display type, and relevant metadata. The user with the HMD can scan and decode the information from the QR code that is overlaid on top of the original video stream and, therefore, configures the physical display automatically. We achieve the duplication of the display video stream by employing a frame grabber capable of capturing a video stream with 1920×1080 at 60 Hz. We then implement a data processing server in Python to encode and send frame

[1] https://github.com/lincolnloop/python-qrcode

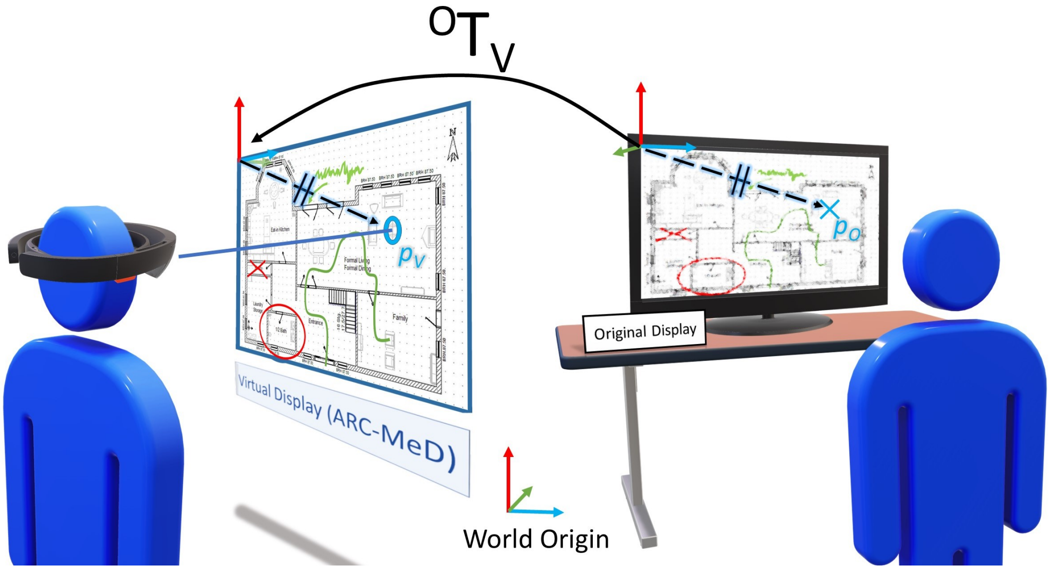

Figure 2. Geometrical Transformations. Users can see the interaction of other collaborators in real-time. Annotations are 2D-projected onto the display or 3D visualized through Augmented Reality on top of the display. When the user chooses to use 3D annotations, the system shows the real display and the pose of the ARC-MeDs within a common world origin. ARC-MeDs transform annotations with $^{O}T_V$ into the other display coordinate system. The dashed black lines depict that the points p_V and p_O have the same pose relative to the origin of the respective display.

data via TCP socket connection. The end-user HMD receives and decodes the data in real-time and displays the content in MR.

3.2. Collaborative Annotation

The intuition of drawing lines as a means for visually assisting verbal communication is intuitive for humans. VR allows users to create annotations in three dimensions through mid-air gestures. Alternatively, lines from 3D gestures can be 3D-2D projected onto a 3D plane hovering in the virtual environment. However, creating precise 3D annotations mid-air is a non-trivial task because, unlike pen and paper, there is no tactile feedback during the drawing process. Further, humans often poorly estimate the dimension of depth. Unconstrained guides (e.g. Smart3DGuides by Machuca et al. (2019)) and constrained guides (e.g. Multiplanes by Machuca et al. (2018)) may improve the user experience.

According to the observations and related work, we recommend and implement annotations with the ARC-MeD as follows: We project annotations made close to the virtual display onto the corresponding 3D plane using a similar approach to Multiplanes. The projection is made using a virtual orthographic camera to compute the 3D to 2D projection based on the equation

$$x = M_{orthographic} \bullet X$$

where X denotes the 3D annotated point in the world coordinate system, $M_{orthographic}$ is the camera matrix of the orthographic projection and x represents the projected pixel coordinate of the virtual display. Finally, the method replicates annotations made at the virtual monitor at the physical monitor and vice versa. The equation for cal-

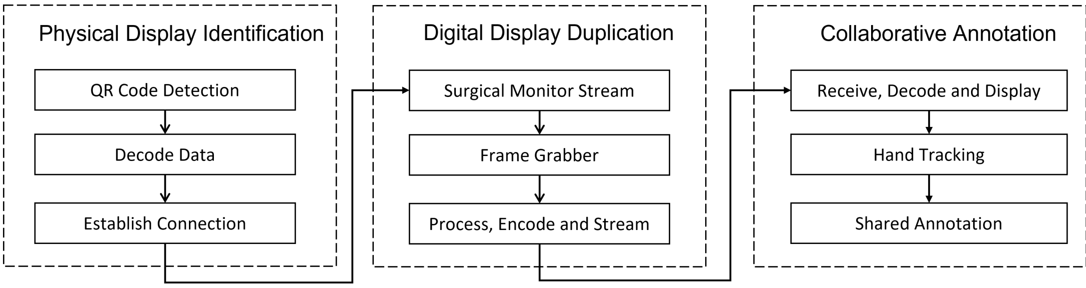

Figure 3. Systematic Overview. ARC-MeD establishes the connection between the physical display and HMD by decoding the QR code on screen. The display content can then be streamed wirelessly. The user is able to manipulate and make annotations on the personal ARC-MeD with hand gestures.

culating the point p_V on the virtual display based on a point p_O in the coordinate system of the original display is

$$p_V =^O T_V \bullet p_O$$

as seen in Figure 2.

As the collaborative system needs to synchronize line annotation across multiple devices, we sample a line with constraints to reduce the number of points representing the final line. In particular, we monitor the stroke direction of the user's input in every frame. As long the user draws draw along a straight line, we describe the line with two points and update the end-point continuously based on the current pen tip. When the user initiates a curve, we sample these points and fit the curvature of the line with a Cat-Mull curve. Finally, we serialize the points and utilize Huffman compression to reduce the network overload for synchronization.

3.3. Interacting with the ARC-MeD

As hand tracking is becoming an integral feature of modern HMDs (e.g., Magic Leap One, Microsoft HoloLens 2, Oculus Quest), we design our system to use hand gestures as the primary input for interaction. The user can move, rotate and adjust the size of the duplicated display by direct touching for near interaction or using a hand ray for far interaction. Our system that integrates ARC-MeDs triggers the routine for drawing annotations when the users pinch their index and thumb so that the distance between the index and thumb finger reaches a set threshold. The system then generates the line at the tip of the index finger. The annotation ends when the user releases the pinching gesture. To prevent false positives for this drawing gesture while manipulating the display, we ask the user to select handedness at the beginning of the application to indicate whether the user is left-handed or right-handed by tapping the corresponding button. The system only allows the dominant hand to annotate and the non-dominant hand to adjust the display.

Prior work has found that magnifications of virtual objects aid users in mixed and virtual environments during high-precision tasks (Qian et al. (2022); Yu et al. (2021)). Therefore, we integrate magnification by allowing users to specify regions on which the ARC-MeD should magnify and focus. In a focused mode, annotations maintain the correct offset towards the full display content so that users can more easily draw annotations on an enlarged canvas.

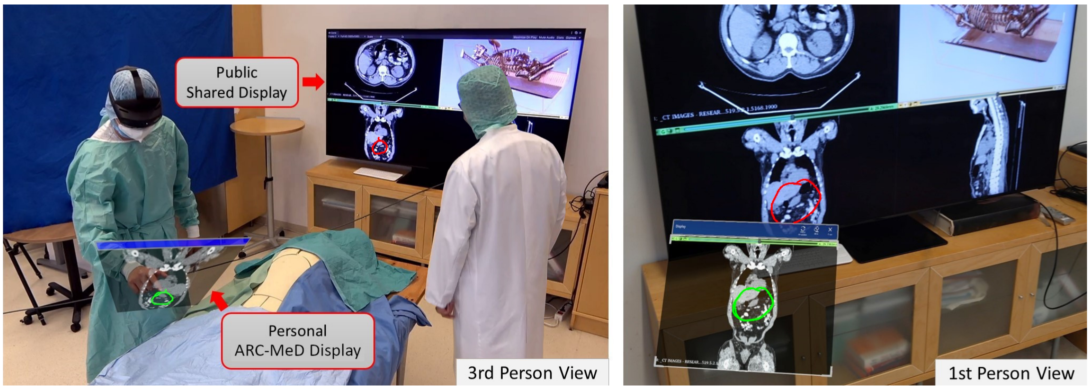

Figure 4. Touch-free interaction with the ARC-MeD. The surgeon may choose to see only a sub-region of the whole screen. The ARC-MeD replicates real-time annotations onto the monitor and make them visible to everyone inside the room. Simultaneously, users can add annotations through touch or mouse input on the large monitor, which are again visible on the ARC-MeD.

4. Exemplary Use-cases

Our concept enables remote collaboration with setups using asynchronous device modalities (VR/AR) in different locations and in close proximity to co-located users (AR/AR). In the following, we present use cases showcasing those collaboration variants and discuss our concept's usage.

4.1. Use Case: Co-located Collaboration in an Operating Room

The first use case highlights a setup with a single large and physical TV screen showing multiple types of information. We demonstrate this setup based on an actual operating room. A large physical monitor displays the most recent acquired X-Ray image, with additional pre-operative or intra-operative imaging. The content of the large monitor is available to all co-located people, including assistant nurses and anesthesiologists. Selected people, such as the operating surgeon, wear an OST-HMD to see individual ARC-MeD (Figure 1). Wearing the HMD, a surgeon interacts with the content of the virtual display completely touch-free. We deployed multiple features to the ARC-MeD: (1) Users can choose a sub-region of the physical monitor rather than the whole display to visualize inside the virtual monitors. (2) Users create line annotations by pinching their thumb and index finger together. (3) The lines are 3D-2D projected onto the virtual monitor and replicated on the physical monitor. The benefits are as follows: Surgeons no longer need to move their heads towards the physical monitor as the content is replicated in front of them virtually. In addition, surgeons and bystanders can use digital drawings on any display, including the physical monitor, to annotate the display in real-time (as seen in Figure 4).

4.2. Use Case: Asymmetric Teleconsultation

An asymmetric telepresence system typically consists of at least two parties. The local users reside within an environment where the system knows the environment's geometry, e.g., knowingly constructed or reconstructed from depth-sensing data. The system transmits the room's geometry to the remote participants. They perceive the space through VR in its original scale, such that they believe they have physically

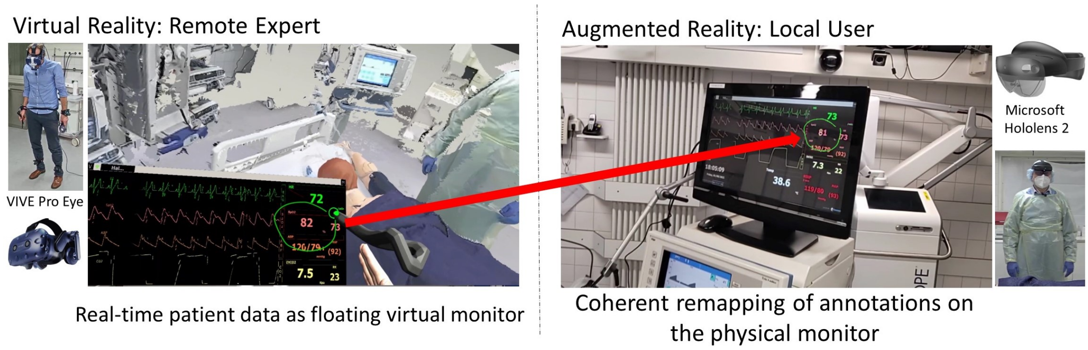

Figure 5. ARC-MeDs in Asymmetric Mixed Reality Teleconsultation. Immersive teleconsultation systems utilize 3D reconstruction of the environment to enable immersive remote collaboration. However, since the environment-capturing cameras are limited in their image resolution and distance to particular objects, displays inside the room are usually textured with a low resolution. By capturing the display content and visualizing it with an ARC-MeD for the remote consultant, it provides a high-resolution view of the display. Additionally, the system automatically transforms all annotations back to the original display position so the local user can see them correctly on the screen.

teleported into the room of the local user.

For our demonstration, we calibrate the extrinsic of six Azure Kinect cameras via bundle adjustment (Alvarruiz Serrano (2014)) and stream their data to a Unity3D app. Next, the app projects the depth images into multiple 3D point clouds. Finally, the app triangulates the point cloud and texturizes it with the acquired color images to receive the final 3D visualization of the room.

Such a telepresence system based on the capture of depth cameras usually is limited by the resolution of the color textures of the 3D reconstruction. Moreover, the reconstruction may contain holes or inaccurate depth, preventing the user from interacting confidently with the visualized information. One of the major concerns in using infrared-based depth cameras is their dependency on the surface material, particularly the reflective index of surfaces, for adequately estimating the depth. Especially, depth cameras that depend on emitted infrared light rarely capture monitors correctly since displays usually deploy infrared absorbing layers in their construction. Therefore, the employment of our concept in such a system has multiple benefits. The live-streaming of the display's content delivers a high-definition view. Therefore, the user is able to read the patient data more clearly than the lower-quality 3D reconstructed display. Additionally, it allows users to increase the size for a closer look at details and enables the creation of shared annotations (see Figure 5).

5. System Evaluation

We evaluated the end-to-end latency by calculating the timestamp difference between the physical display and the ARC-MeD. We took measurements of the latency and application refresh rate under multiple streaming resolution. As shown in Figure 6, we observed that the system performance monotonously decreases as the resolution increases. We found that the end-to-end latency for duplicating a 640×480 display is 212.8±68.9 ms, for a 1280×720 display is 296.7±147.4 ms, and for a 1920×1080 display is 351.2±115.9 ms. Based on the results, we recommend choosing 640×480, as it maintains a near 60Hz refresh rate and negligible streaming latency to provide a good user experience for the MR application. For display resolution higher than this

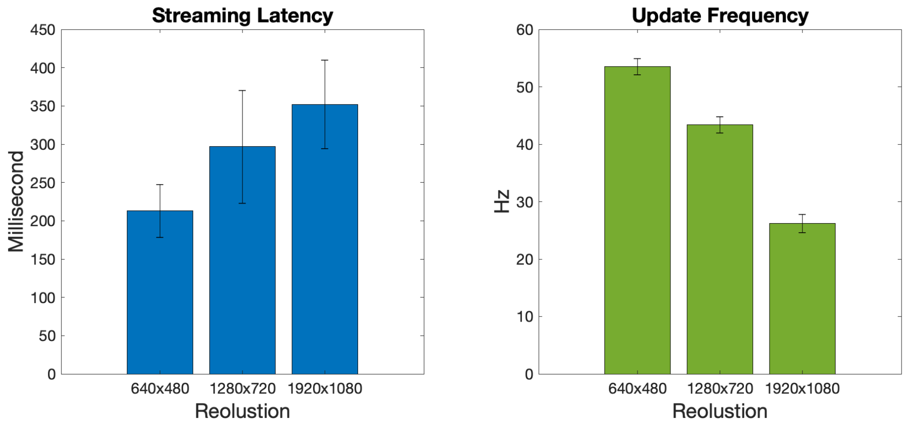

Figure 6. System Performance. The end-to-end latency and update frequency under different configurations in ARC-MeD.

value, ARC-MeDs may scale down the resolution of the video stream to achieve the ideal performance.

6. Discussion & Future Work

ARC-MeDs provide a novel communication tool that connects all people within the operating room. Annotations are replicated and shared instantly across multiple display mediums, while the content streaming from the primary monitor only introduces minimal negligible latency for most intra-operative imaging modules. For a truly immersive user experience, medical devices should provide access to their display content or directly integrate a local network interface that our ARC-MeD systems can access. The personalized ARC-MeD would intuitively switch between the most relevant screen depending on the user's role within the operating room. An integrated interface inside established medical devices would enable a wide range of functionality. For example, next to the proposed method of ARC-MeDs for creating annotations, our virtual monitor could provide additional information that is an extended screen added to the device's main screen or serving as a magnification glass for specialized detail views.

Based on our current implementations, we observe remaining challenges for a fully deployable system in the OR. In particular, creating accurate annotations remains an open research field since the hand-tracking capabilities of the AR HMD are optimized towards visual fidelity rather than stability and accuracy. For example, Dudley et al. (2018) proposed using tap lines to more accurately trace a given 3D shape. However, users would need to continuously perform the tab-gesture while complex shapes such as free-hand texts or smooth curved lines will be cumbersome to draw. Therefore, tracked controllers in pen shape could remedy most tracking inaccuracies with hand tracking. Such devices would, however, introduce hardware that needs to be sterilized and actively touched when used inside the OR.

With the co-registration of the patient, the patent's imaging data, and ARC-MeD users, we envision the possibility for HMD users to annotate in 3D directly on the patient's anatomy. At the same time, non-HMD users can see the correctly projected annotations on the 2D physical display. Furthermore, 2D annotations made by mouse input on touchscreen input can intelligently be visualized directly onto the patient in 3D. This capability can greatly promote and boost collaboration among all users.

Our next plan is to do a multi-user study with clinicians to study the annotation accuracy with different sizes of the displays and evaluate the usability with the current setup and gather feedback to further improve the system.

7. Conclusion

We proposed the concept of Augmented Reality Collaborative Medical Displays (ARC-MeDs) for connecting people within the surgical operating room or a remote telepresence setup with a multi-display system. By allowing medical experts to interact with a mobile virtual display, they can use free-hand annotations on shared screen contents to actively communicate with their colleagues. Furthermore, since ARC-MeDs are virtually hovering in the air, users can position them freely without physical constraints. We evaluated the system performance and demonstrated in two scenarios: a co-located scenario and an asymmetric 3D teleconsultation system. We believe that when AR HMDs further mature for use in medical environments, our proposed method will provide an essential tool for interconnected communication with internal and external collaboration parties.

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