CoLT: Enhancing Collaborative Literature Review Tasks with Synchronous and Asynchronous Awareness Across the Reality-Virtuality Continuum

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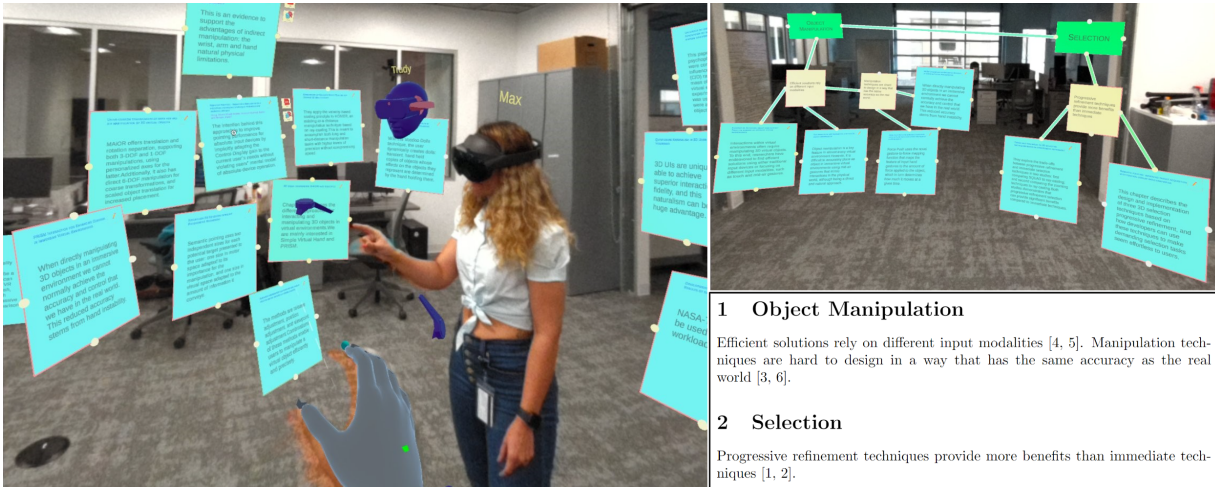Department of Computer Science, Virginia Tech, Blacksburg, VA, USA

Figure 1: Two colocated AR users and one VR user collaborating with annotations made both in the real and virtual world (left). Part of the final layout of the collaborative literature review (top-right). LaTeX file output from the layout (bottom-right).

ABSTRACT

Collaboration plays a vital role in both academia and industry whenever we need to browse through a big amount of data to extract meaningful insights. These collaborations often involve people living far from each other, with different levels of access to technology. Effective cross-border collaborations require reliable telepresence systems that provide support for communication, cooperation, and understanding of contextual cues. In the context of collaborative academic writing, while immersive technologies offer novel ways to enhance collaboration and enable efficient information exchange in a shared workspace, traditional devices such as laptops still offer better readability for longer articles. We propose the design of a hybrid cross-reality cross-device networked system that allows the users to harness the advantages of both worlds. Our system allows users to import documents from their personal computers (PC) to an immersive headset, facilitating document sharing and simultaneous collaboration with both colocated colleagues and remote colleagues. Our system also enables a user to seamlessly transition between Virtual Reality, Augmented Reality, and the traditional PC environment, all within a shared workspace. We present the real-world scenario of a global academic team conducting a comprehensive literature re-

view, demonstrating its potential for enhancing cross-reality hybrid collaboration and productivity.

Index Terms: Human-centered computing—Virtual Reality—Augmented Reality—Reality-Virtuality Continuum; Synchronous Collaboration—Asynchronous Collaboration—Remote Collaboration—Colocated Collaboration

1 INTRODUCTION

In today's interconnected world, technological advancements have significantly transformed how we interact with information and each other. The advent of the Internet brought people together metaphorically, while recent developments in Mixed Reality (MR) technologies are bridging the gap between physical and virtual realms, fostering an almost tangible level of interconnectedness. With real-time eye and hand tracking capabilities, users can now seamlessly interact with virtual elements, mimicking their interactions with real-world objects.

Using immersive technologies as a means to collaborate amongst team members has become an interest of researchers and business stakeholders alike in recent years [4]. With improvements in hardware and software capabilities of MR devices such that they are more commercially viable for consumers, the ability to share environments, represent persons, and capture interactions are the strengths of MR applications that promise believable and useful future collaborative tools [15]. Similar to existing computer-mediated communication tools available to users today (e.g., Zoom [1], Microsoft Teams [2]), collaborative MR applications empower colocated [9], remote [11],

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[1]https://zoom.us/
[2]https://www.microsoft.com/en-us/microsoft-teams/group-chat-software

and the combination of remote and colocated peers to work together toward a common goal collectively [18]. Distinguishing them further from equivalent use case 2D telepresence solutions, MR systems provide a means by which, even in the case of geographic separation, users can feel more present with their remote peers [19] and alleviate the known difficulty in maintaining references between content and user video [16].

Although head-worn displays are becoming more commercially accessible, they are not necessarily readily available as household or business devices. For this reason, cross-device capabilities enable these MR applications to work not only on AR/VR headsets but also tablets, smartphones, and existing workstation computers and laptops [2, 7, 12]. Further capabilities of such technology include the ability to work both synchronously [15], when time zones and meeting schedules align, and asynchronously [8], where guided tours by peer avatars can be generated to inform of changes that have transpired at a different work schedule entirely.

Cross-reality analytics is one concept that looks at how to collaborate between users in different modalities of the Reality-Virtuality Continuum (RVC) [10] or transition between the various levels of MR [5, 14]. One example of cross-reality analytics is using a portal that allows the user to see their surroundings and increase their bodily awareness [1, 6]. In our design solution, we explore ways to exchange data across realities, and facilitate communication to further the goals of the group.

Academia represents one of the most vibrant domains where cross-border collaboration thrives. Research teams from diverse laboratories continuously join forces to ideate, design, and develop projects, later publishing papers on their findings, collectively advancing the frontiers of knowledge. While several collaboration tools exist, each catering to distinct aspects of the research process, our design solution focuses on facilitating a collaborative literature review among researchers with the ultimate objective of producing a comprehensive survey paper. Within a typical research project group, there may be researchers with varying levels of access to MR (Mixed Reality) technology, ranging from state-of-the-art MR devices to none at all.

We propose a design solution that recognizes the diversity in user access along the RVC - comprising the real world, Augmented Reality (AR), and Virtual Reality (VR) [14]. We introduce an innovative approach that enables users to import their annotations, generated through reference management systems, into an immersive space accessible from all three RVC stages. In this environment, users have the capability to collaborate effortlessly by sharing and organizing annotations. They can enhance existing annotations together or collaboratively create new ones. Additionally, users can work together to arrange their annotations by moving them, creating hierarchies, and developing layouts. These organized annotations can later be transformed into a structured LaTeX file, complete with sections, paragraphs, and citations. To validate the effectiveness of our design solution, we present a scenario involving a geographically dispersed group of researchers with different levels of access to MR technology. The scenario demonstrates how they effectively leverage the cross-reality collaborative platform, Collaborative Literature Review Task Solution (*CoLT* for short), to foster fruitful collaboration within the literature review process.

In this paper, we delve into the conceptual underpinnings of our cross-reality collaborative literature review platform. We discuss the technical aspects of our solution, addressing the challenges associated with accommodating diverse MR devices while ensuring an inclusive and seamless user experience. Moreover, we outline the benefits and potential implications of adopting such an innovative approach for fostering cross-reality cross-border academic collaboration.

2 DESIGN MOTIVATION

In this section, we present a real-world scenario, break down the tasks involved, and analyze the requirements to facilitate the completion of the tasks.

2.1 Scenario

It is the year 2025 and the students of a human-computer interaction lab at Real University in the United States have decided on various activities they will participate in during their summer semesters. One member, Peter, has relocated out of the state in order to work as an intern at the renowned technology firm, Pear, while Brittany and Nick have stayed at the university to continue their research efforts. Finally, Miles has decided to take a trip abroad to Europe to explore potential post-doc opportunities. Leading up to the summer, these four labmates find themselves discussing potentially publishing at an upcoming conference but realize they will not have enough time to complete their literature review prior to departing for their respective destinations. Furthermore, with their relocation, not all members will have access to the same hardware technologies and working schedules, further complicating the ability to fully coordinate work efforts and communicate the work they have conducted toward the paper meaningfully. However, using CoLT, the team is able to collaborate seamlessly across environments, time zones, and available hardware resources.

Due to concerns about bringing expensive technologies abroad, Miles does not have a headset with him during his travels. Instead, while at his hostel, Miles launches CoLT from his laptop to read and annotate the papers aggregated by the group prior to their departure from the university. He creates some preliminary sections to group documents he finds with similar contributions after perusing them, providing brief notes summarizing each document, before continuing on with his day visiting nearby research labs. Back in the United States, Peter, Brittany, and Nick meet during a scheduled working session to review literature together in the CoLT system. At the lab, Brittany and Nick use AR headsets to maintain sight of one another as they work together in the same room with the documents. Peter joins using his standalone VR headset, able to observe, communicate, and interact with Brittany and Nick via their respective avatar representations. Together, they review the contributions from Miles prior to continuing and expanding on the sections he initially detailed, linking annotations together to weave a narrative together for their work.

With the *CoLT* system, the geographically distributed students are able to complete the literature review, regardless of time differences and technology availability. It supplements the existing methods of content sharing using annotations by providing the sense of embodiment and presence that typify MR via avatar representations of collaborators and the recreation of their interactions with the data seamlessly with visual effects.

2.2 Task Requirements

The scenario outlined in Section 2.1 reveals two overarching tasks that users seek to accomplish. Firstly, they require a tool that enables them to read, annotate, and organize papers to generate ideas pertaining to a specific field of research. Secondly, they aim to share their findings with fellow researchers to obtain feedback, refine annotations, reorganize papers, and further develop their ideas collaboratively.

Given that the ultimate outcome of this scenario is a structured literature review section, we draw inspiration from the typical structure of research papers to analyze the requirements of the first task. Each section of a paper follows a specific format, comprising a **title**, followed by one or more paragraphs containing **statements** supported by citations of relevant **papers** as evidence. Hence, to successfully complete the first task, the system needs to allow users

to create and organize the following artifacts: title, statement, and paper.

Users need to browse and organize these papers effectively to formulate robust, well-supported statements. Concurrently, users require access to pertinent papers as evidence to bolster their statements. Collaborators can play a vital role in both of these aspects. To facilitate effective collaboration, they need access to the titles, statements, and papers organized by fellow researchers. In situations where collaborators face challenges in finding a common time and place to meet, they should be able to share these artifacts remotely (for geographically dispersed collaborators) and asynchronously (for collaborators with different work schedules). Hence, to successfully accomplish the second task, users must engage in different levels of collaboration: **remote-synchronous**, **colocated-synchronous**, and **asynchronous**. Each mode of collaboration caters to specific scenarios, ensuring efficient communication and cooperation among researchers, irrespective of their geographical or temporal constraints.

3 DESIGN SOLUTION

In this section, we detail our solution based on the requirements defined in Section 2.2.

3.1 Artifacts

Artifacts are the virtual elements that the users need to complete the first task, organizing a literature review section. We identified three types of artifacts required for this task: papers, statements, and titles.

Papers During the process of reading a printed paper, researchers often jot down their personal notes on the paper's margins. Based on this practice, most reference manager software platforms offer note-taking features, allowing users to efficiently annotate and organize their research materials for easy access and collaboration.
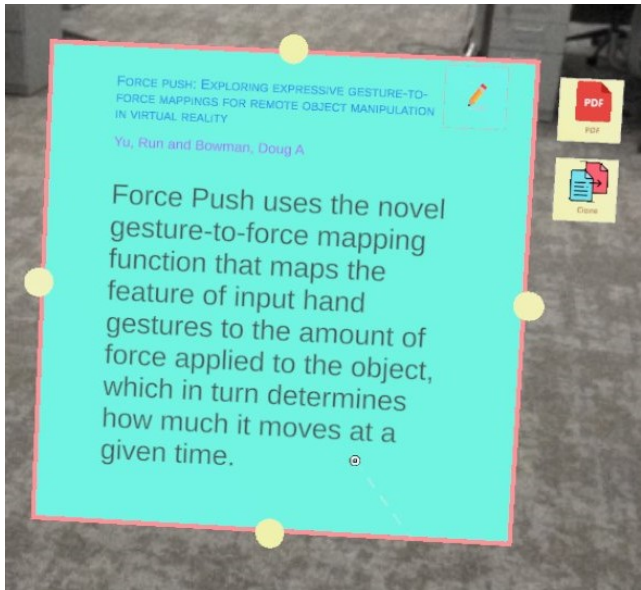

Figure 2: Paper representation in *CoLT* shows the title, author names, and custom-made notes written by users. Users can edit the note content by pressing the button on the top-right. They can also view PDF, or clone the paper by using side-menu.

In the case of *CoLT*, papers are represented by these custom-made notes that are imported from the desktop reference management software. They resemble sticky notes, placed against a background. Additionally, the system loads the paper's title, authors' names, and the full paper PDF file. Hovering over a paper will display its authors, and a menu with three options: "Edit", "Clone", and "PDF"
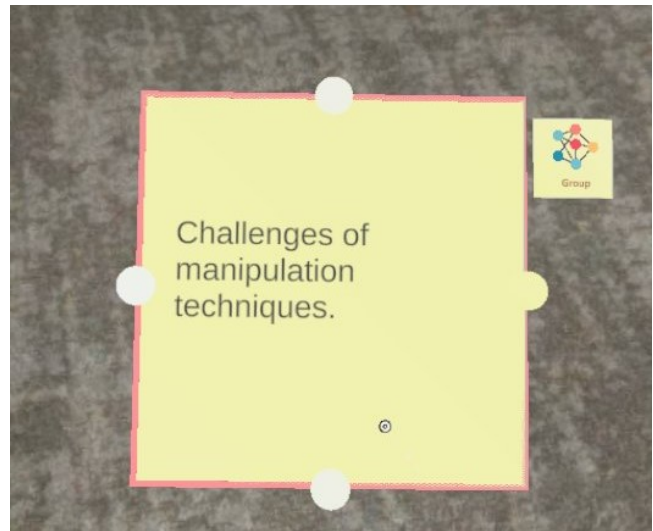

Figure 3: Statements made in *CoLT* to represent discussions about a group of papers inside a Section. The 'Cluster' button triggers semi-automated identification of a cluster of papers around the statement.

Figure 4: Title made in *CoLT* to represent the Section titles in research papers.

(as in Figure 2). By selecting the "Edit" option, the user is able to modify the notes associated with the paper. Users can create a clone of the paper by pressing the "Clone" button. This feature comes in handy when a single paper is referenced in two or more sections. Finally, clicking the "PDF" button will open a side view of the full paper, allowing the user to browse and read it.

However, reading in AR/VR still suffers from reduced response time [13], and increased cognitive load [3]. As a result, we anticipate that users of *CoLT* will continue to utilize their 2D displays for reading PDFs, while immersing themselves in the AR/VR environment to focus on smaller annotations and the collaborative process. However, the full paper still remains readily accessible, ensuring users can quickly reference essential information whenever needed. This hybrid approach aims to optimize reading efficiency and enhance collaborative discussions, providing researchers with a comprehensive and versatile platform for academic collaboration.

Statements In *CoLT*, users have the ability to write down the summary of findings related to one or more papers that we refer to as *statements*. Users have the flexibility to attach a statement to any one or more papers of their choosing, allowing for versatile and personalized organization of their research materials and insights.

Titles Users have the option to write down the title of a section that is associated with one or more statements and/or papers. This feature allows for better organization and categorization of information.

3.2 Interactions

Move *CoLT* employs the hand-tracking capabilities of AR/VR devices to allow interaction with artifacts using natural hand gestures. They can grasp an artifact by pinching it with their index finger and thumb, enabling them to move it around while maintaining the pinching gesture. Releasing the two fingers will free the artifact and allow it to float in the 3D space. Additionally, users can use the pinching gesture to interact with buttons within the system.

Connect Users have the capability to establish connections between artifacts, thereby determining the sequence of their arguments. This feature proves valuable when exporting the 3D layout to a LaTeX file. Artifacts can be connected with each other using two different methods: manual and semi-automatic.

Manual Each artifact is equipped with four access points, one on each side (see Figures 2, 3, 4). Users have the ability to establish a relation between artifacts by grasping an access point in one artifact and moving it to another access point on a different artifact. When two compatible access points come into contact, a visual outline provides feedback to indicate a valid connection. Upon releasing the access point, a connection is established between the two artifacts, visually represented by a thin cylindrical line.

Semi-automatic Additionally, users have the option to rely on the system for connecting artifacts. Each *Statement* is accompanied by a *Cluster* button (see Figure 3). When this button is pressed, the system identifies the cluster of papers surrounding the Statement with the Dirichlet Process Mixture Model clustering algorithm [17]. As a result, the system visually represents the identified cluster by connecting the artifacts with thin cylindrical lines (see Figure 1).

In both types of connections mentioned above, users retain the ability to manually link titles with other titles, statements, and papers by attaching the access points.

Export When the sensemaking process is complete, users have the ability to export the layouts from the immersive space to a LaTeX file. During this process, all the *Titles* will be transformed into *Sections*, and the individual statements will be represented as paragraphs under their respective sections, with the list of papers presented as citations.

The order of the sections in the LaTeX file will mirror the sequence in which Titles were originally connected with each other. The order of the paragraphs will follow the connection made between different Statements. The paper citations will follow the connections created between the statement and the paper. For a visual example of this conversion from the immersive space to the LaTeX file, refer to Figure 1.

3.3 System Overview

We have implemented *CoLT* using Unity v2021.3.12 along with the Mixed Reality Toolkit [3] for hand gesture recognition and interaction, and PUN 2 [4] for networking capabilities. Our design ensures that *CoLT* can run on both Quest 2 [5] for a VR experience and Quest Pro [6] for both VR and AR experiences. It can also run on a standalone Personal Computer (PC), allowing users to join even if they do not have a Head-Worn Device (HWD) available.

To facilitate text entry, users can utilize a physical keyboard connected to the HWD via Bluetooth. The keyboard is placed on a rolling table, granting users the freedom to move it around as needed for convenience and comfort. In both AR and Desktop conditions, the relative position of the keyboard is easily noticeable. However, in VR, users might encounter challenges returning to the keyboard after completing non-typing activities. This necessitates innovative

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methods to provide visual feedback of the physical keyboard, like selective passthrough [6]. However, for this solution, we maintain consistency for all users by using the same type of text entry solution.

We employed a hand-registered menu to use different features in the system. Upon running the application, the user can use the menu to log into (see Figure 5) their reference management software to get access to their personal set of papers. After successfully logging in, the hand-registered menu displays options to write statements, write titles, and export layouts (see Figure 6).

Figure 5: The hand-registered menu for logging into *CoLT* with the reference management software credential to access all personal annotations.
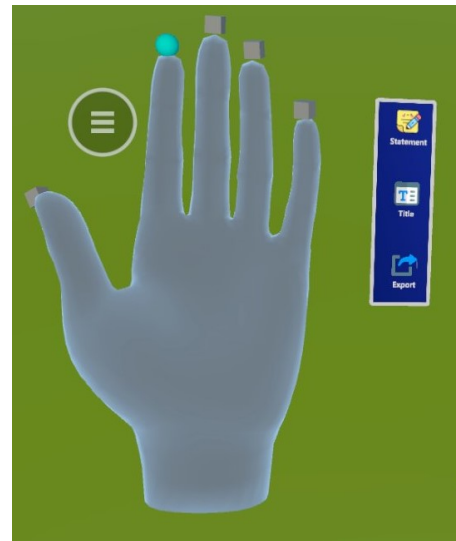

Figure 6: The hand-registered menu for creating titles, creating statements, and exporting layouts. This menu is available after logging into the system.

3.4 Synchronous Collaboration

Multiple users can participate in *CoLT* to collaboratively share and discuss their papers. They have the flexibility to join either in a colocated physical space or from remote locations.

In a colocated physical space, users can interact with the system and each other while being physically present in the same location.

This facilitates face-to-face discussions and enhances the collaborative experience.

On the other hand, users also have the option to join the system from remote locations. With the networking capabilities, remote participants can interact with the shared layout, access papers, and engage in discussions (using built-in speakers on the HWD) with other users, even if they are geographically dispersed. This capability promotes seamless collaborations, regardless of the users' physical locations.

3.4.1 Remote Collaboration

In this scenario, the users are located in two or more different physical spaces, and they have the option to join *CoLT* through two different methods: using a Head Worn Device (HWD) for natural hand gesture interaction or via a PC for traditional keyboard and mouse interaction.

Join with HWD When users join with the HWD, they can navigate the shared space by physically walking around and interacting with the artifacts using natural hand gestures. They also have the choice to experience AR, where they can view real-world surroundings along with the shared digital artifacts. In this setup, remote collaborators will be visually represented by virtual avatars (see Figure 1), while the colocated collaborators will not have any virtual representation. If the users opt for VR experience, they will be fully immersed (see Figure 7) in a virtual room, and all collaborators, both remote and colocated, will be virtually represented by their avatars.
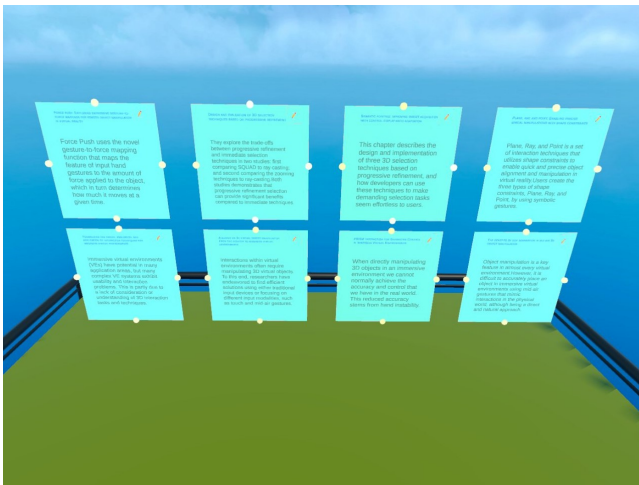

Figure 7: The Point of View of a VR user. The virtual floor has railings on the edge of tracked space to prevent bumping into walls from the real world.

Join with PC Alternatively, users can join *CoLT* through their personal computers. They will use the WASDQE keys on their keyboard to move around the environment, and the left mouse button to interact with artifacts and system buttons. Since the hand-registered menu is not accessible to PC users, they can access the menu options by a combination of keys on the keyboard. While holding the *alt* key, the user can press the following keys to access the available features: N (set name), L (log in), S (create statement), T (create title), and E (export layout). In this case, PC users will be considered remote collaborators and represented within the system as virtual avatars.

3.4.2 Colocated Collaboration

In this setup, users can physically meet in person and use *CoLT* to collaborate. To achieve a colocated experience, *CoLT* can be calibrated to ensure that all users see the same digital artifacts in the same physical space. The calibration process is as follows:

Alignment with Physical World To enable a colocated experience, one approach is to use shared spatial anchors, which are world-locked frames of reference that persist in their location in the physical world across different sessions. However, even though they appear in the same physical space, their virtual location depends on the orientation of each user's headset.

In *CoLT*, we adopt a networked environment where the global positions of all artifacts are shared with other users in real-time. Utilizing spatial anchors to fix artifact positions would require changing their global positions for all users, leading to an irregular and inconsistent experience. To address this, we devised a workaround to provide a smooth colocated experience.
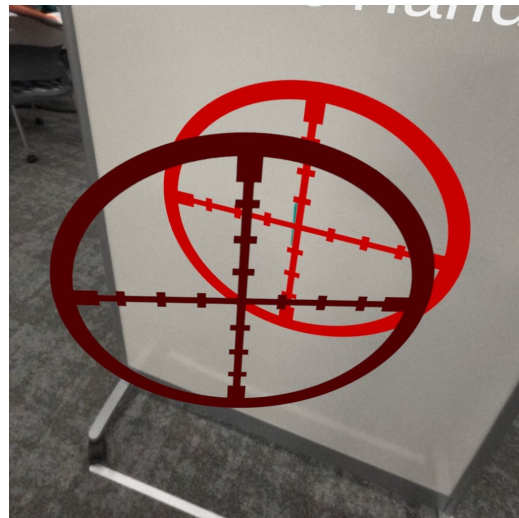

Figure 8: The red crosshair (overlaid on a crosshair drawn on the whiteboard) indicates the current alignment status. If it does not align with the physical anchor, the user can redo the alignment process with the darker crosshair as visual feedback.

Upon logging in, each user will observe a crosshair positioned about half a meter in front of their body. This crosshair will move along with the user, maintaining a constant distance from them and a consistent height from the floor. To calibrate the system, users need to approach a whiteboard or a predetermined vertical object in the physical space where a similar crosshair is drawn or placed at the same height (refer to Figure 8).

The calibration process involves the following steps:

1. The user stands in a way so that the real-world crosshair and the virtual crosshair align with each other.

2. The user then presses a predefined button on their controller to recenter the orientation of the HWD.

3. Other colocated users follow the same calibration steps.

Recentering the HWDs in reference to the same physical position ensures that all users see the same virtual artifacts in the same global position within the shared physical space. After calibration, the crosshair disappears, and the users find themselves in the shared environment with the colocated experience established.

It's important to note that the physical crosshair can be replaced with any vertical object in the physical space that all colocated collaborators agree upon, serving the same purpose for calibration.

3.5 Asynchronous Collaboration

In *CoLT*, the layouts created by users are persistent and shared among all users. Any modifications made to the layout, as well

as the content of all artifacts, are automatically saved on a cloud account created with Playfab Azure [7]. This cloud storage is secured by a two-factor authentication system, ensuring that only the lead author has access to it.

The persistent nature of the system enables users to engage in asynchronous collaborations with other users. This means that multiple users can work on the same layout at different times, and all changes are synchronized and accessible to all authorized collaborators.

3.6 Transition Across Realities

The flexibility of *CoLT* allows users to seamlessly transition from using their PC to any of the HWD conditions. If a user is working on the PC and wants to switch to an HWD, they can simply put on the HWD at any time. The asynchronous feature ensures a smooth transition, allowing them to pick up right where they left off on the PC.

When using the HWD, users have the convenience of transitioning between Augmented Reality (AR) and Virtual Reality (VR) conditions by tapping twice on the side of the HWD. This single-gesture functionality enables users to effortlessly switch between AR, where they can see the real world along with digital artifacts, and VR, where they are fully immersed in the virtual environment. This flexibility caters to the users' preferences and allows them to adapt the experience to their specific needs at any moment.

4 CONCLUSION

In summary, our design proposes a cross-reality platform for cross-border academic collaboration. Users can read, annotate, and organize papers, fostering idea generation. The system accommodates users joining from three different stages along the Reality-Virtuality Continuum (RVC). Researchers can collaborate with each other to connect artifacts, determine argument sequences, and export 3D layouts to LaTeX files. This inclusive approach enables remote, colocated, and asynchronous collaboration, reimagining academic research possibilities. The collaborative cross-reality literature review platform has significant potential to accelerate knowledge dissemination and drive innovation across disciplines. A demonstration of the system is available online [8].

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