Where We Stand and Where to Go: Building Bridges Between Real and Virtual Worlds for Collaboration

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ABSTRACT

Cross reality has redefined how individuals interact in the virtual and physical realms, offering a comprehensive paradigm for communication and collaboration. A rigorous examination of the literature from ACM, IEEE, SCOPUS, and ScienceDirect databases was conducted using a focused search string, resulting in the review of 42 relevant papers as of July 10th, 2023. Our analysis provides an understanding of the current state of cross reality collaboration across various fields, including hardware and software technology, applications, and hybrid user interfaces. Future research directions such as addressing non-adopters, implementing 'Privacy by Design' principles, and enhancing latency reduction are highlighted. We hope that our paper will serve as a stepping stone for researchers and practitioners aiming to develop novel cross reality collaboration experiences.

Index Terms: 500 [Human-centered computing]: Interaction design—Interaction design process and methods; 500 [Human-centered computing]: Interaction design—; 500 [Human-centered computing]: Collaborative and social computing—;

1 INTRODUCTION

With rapid technological advancements, the landscape of human-computer interaction has undergone transformative changes. Augmented reality (AR), virtual reality (VR), and mixed reality (MR) have emerged as cutting-edge technologies, revolutionizing the way individuals perceive and interact with the digital world. These immersive technologies have the potential to create seamless digital experiences by blending the virtual and the physical, redefining the boundaries between them, and offering a new paradigm for collaboration and communication.

The term "cross reality" has become an umbrella concept merging AR, VR, and MR. As opposed to extended reality (XR), which is simply a term encapsulating the various reality technologies, cross reality extends the possibilities beyond individual realities, combining elements from each domain to create novel, all-encompassing experiences. Hybrid user interfaces (HUIs) play an important role in providing a more flexible and versatile user experience for cross reality applications. When cross reality is incorporated into various fields, from education and training to healthcare and entertainment, the potential for improving collaboration and teamwork in virtual environments becomes evident. The insurgence of cross reality technology opens up new possibilities for collaboration, enabling participants to overcome the barriers of physical distance and fostering a deeper sense of presence and co-presence.

In this paper, we examine the existing literature in the ACM, IEEE, SCOPUS, and ScienceDirect databases with the following search string: "("augmented reality" OR "virtual reality" OR "mixed reality" OR "VR" OR "AR" OR "MR") AND ("cross reality") AND ("collaboration")" on July 10th, 2023. We found 98 papers; we eliminated 1 paper because it was not written in English, 19 were repeated in more than one database, and 36 were not related to the topic. In total, we examined 42 papers to gain a better grasp of the current state of the domain and highlight potential future research directions.

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2 CREATING TECHNOLOGY FOR CROSS REALITY COLLABORATION

2.1 Software Architecture

Several papers contribute to the creation and development of cross reality collaboration by exploring different aspects of XR technologies and their applications by means of novel software. In Huh et al.'s "XR Collaboration Architecture based on Decentralized Web" paper, a decentralized web-based collaborative cross reality framework is proposed to address challenges in face-to-face collaboration within 3D XR contexts [17]. Through an offline-first strategy, XR content and interactions are synchronized among local users, ensuring resilience to network latency and failure. In another research titled "A Nested API Structure to Simplify Cross-Device Communication" the *R*esponsive *O*bjects, *S*urfaces, and *S*paces (ROSS) API is introduced as a powerful toolkit for cross-platform and device application development, particularly in tangible user interfaces (TUI) [39]. In the same vein, "VRception: Rapid Prototyping of Cross-Reality Systems in Virtual Reality" presents VRception Toolkit, a multi-user toolkit for quick and efficient prototyping of cross reality systems in VR while addressing technical obstacles and expediting the iteration process [12]. Additionally, "Webizing Collaborative Interaction Space for Cross Reality with Various Human Interface Devices" proposes a method to support web-based collaborative cross reality development, integrating user authentication, session management, and human interface device interaction through an interaction adaptor [33]. Reilly et al. introduce TwinSpace, a flexible software architecture that fosters seamless interaction between real and virtual collaborative spaces through robust connectivity and centralized management, as exemplified by two case examples: activity mapping and a collaborative game [30]. Polys et al. proposed a framework that can support Ubiquitous Computing and Mirror Worlds for online multi-entity messaging communication [27]. "Exploring Bi-Directional Pinpointing Techniques for Cross-Reality Collaboration" explores two systems that enable cross reality interaction. The study finds that more disruptive techniques are preferred and more effective for pinpointing objects [26]. Together, these papers propose novel software for the advancement of cross reality collaboration, enabling richer and more immersive experiences across different realities.

Among papers on software architecture for HUI and cross reality, there are three that stand out. In the first article, the authors propose a ROSS API that facilitates real-time data exchange across ROSS-enabled devices, allowing, for instance, a mobile device to control a desktop application [39]. Secondly, in "Fusality: An

Open Framework for Cross-platform Mirror World Installations", researchers enable mapping of visitors' positions into a virtual mirror world, which can then be visualized in various forms remotely or via web client [27]. Lastly, "TwinSpace: an Infrastructure for Cross-reality Team Spaces" introduces a connectivity layer linking physical and virtual devices, with a central service overseeing these mappings [30].

2.2 Facilitating Analysis for Cross Reality Systems

The papers in this section provide valuable insight into the analysis of cross reality systems and collaboration, shedding light on various aspects of transitional interfaces and immersive experiences. Schröder et al.'s "Collaborating Across Realities: Analytical Lenses for Understanding Dyadic Collaboration in Transitional Interfaces" investigates analytical tools that are derived from an exploratory study focusing on transitional collaboration and transitional interfaces (TI) [32]. This is done to gain insights into the role of awareness cues, verbal communication, task loads, and the cost of device switching in influencing user performance and perception of transitional collaboration. The paper titled "A Framework for Analyzing AR/VR Collaboration" introduces the cross reality collaboration framework (CRCF), which enables the analysis of different configurations for interaction elements for a given system or set of systems [37]. Furthermore, the paper "ReLive: Bridging In-Situ and Ex-Situ Visual Analytics for Analyzing Mixed Reality User Studies" presents ReLive, a mixed-immersion framework designed for analyzing user studies in MR [16]. By integrating both immersive and non-immersive analytics, ReLive demonstrates the advantages of bridging these approaches, contributing to the fields of immersive analytics and transitional user interfaces.

2.3 Responsible XR

It is essential to recognize and address the ethical, social, and psychological implications associated with collaborative XR deployment. The papers within this category discuss concerns related to data privacy, user safety, and human experience. In a semantic analysis of vulnerabilities, potential cyber threats, and attacks associated with XR, a research paper titled "A Systematic Threat Analysis and Defense Strategies for the Metaverse and Extended Reality Systems", presents taxonomies on XR cyber threats and defensive measures to guide researchers, developers, and policymakers to mitigate these risks [28]. Furthermore, Abraham et al.'s "Implications of XR on Privacy, Security and Behaviour: Insights from Experts" investigates potential issues concerning security, privacy, and influence on behavior that arise with the widespread use of XR. Through expert focus groups, the study uncovers challenges such as users undervaluing their XR data and increased vulnerabilities, leading to a set of recommendations for building safer and more private XR systems [1]. When it comes to a cognitive framework or a philosophical perspective for challenges that have an impact on human identity, "Syncretic Post-Biological Digital Identity: Hybridizing Mixed Reality Data Transfer Systems" asserts the necessity of a syncretic approach, merging diverse fields, to understand our evolving identity within a 'post-biological' context. As we become entwined with AR, virtual environments, and biological systems, our identities and our understanding of cybernetic systems must adapt. [36].

2.4 Cross Reality Interaction and Interfaces

In this section, we summarize papers that investigate the synergy of various XR systems that offer novel opportunities for communication, information sharing, and shared decision-making.

Fuks et al. present a novel approach to cooperation in their study "Collaborative Museums: An Approach to Co-Design". They present a systematic co-designing process characterized by ethnography, co-creation workshops, and rapid prototyping, which brought innovation in ideas that support mixed presence collaboration and social interaction, and enhancement of user experience for a wide range of profiles [11]. Sasikumar et al., on the other hand, leverage existing technologies with XRTeleBridge, enabling participants using a webcam or head-mounted display (HMD) to embody 3D avatars and interact with real-time natural gestures and eye gaze into conferencing platforms like Zoom [31].

To enhance user experience and usability, innovative design solutions have been proposed. Wang et al. extract important design insights on the preservation of a user's sense of presence in VR while interacting with the physical world by studying a prototype called "RealityLens", a user interface that features custom scaling, placement, and activation methods [38]. More traditional mobile displays also play a key role in cross reality interactions. Two such interactions are examined in "Mobile Displays for Cross-Reality Interactions between Virtual and Physical Realities". "Substitutional Display" is a passive haptic interface that allows the movement of virtual artifacts by both VR and physical reality (PR) users, and "Virtual Artifact Handover" enables the VR user to transfer virtual artifacts onto the PR user's mobile display [34]. Additionally, "Towards Cross-Reality Interaction and Collaboration: A Comparative Study of Object Selection and Manipulation in Reality and Virtuality" by Zhang et al. reveals balanced performance in accuracy, completion time, and user workload in VR, as opposed to biased performance in PC and tablet experiments [42].

When developing interactions in cross reality, design for presence and immersion avoids disengagement and cognitive dissonance. By prioritizing the user experience and ensuring that participants feel fully immersed and connected in the virtual environment, it is possible to minimize potential feelings of detachment and discomfort. Effective design for presence and immersion fosters a seamless integration between the physical and virtual worlds, creating a cohesive and enjoyable cross reality experience for users [27]. Moreover, remaining mindful of the importance of presence and immersion in cross reality applications can also help prevent potential missteps. For instance, Wu et al. find three common design concerns related to collaborative cross reality connectivity in object manipulation, avatar navigation, and tangible user interfaces through the use of physical objects and interactive table interfaces and suggested solutions to them in their paper: "Tangible Navigation and Object Manipulation in Virtual Environments" [40]. Additionally, in ""Nice to See You Virtually": Thoughtful Design and Evaluation of Virtual Avatar of the Other User in AR and VR Based Telexitence Systems", Pakanen et al. find that users prefer photo-realistic full-body human avatars in both AR and VR for their human-like representation and interactive offerings [25]. Further enhancements in collaborative virtual environments are also studied by enabling AR and VR users in different locations to interact beyond first- and third-person perspectives through the use of a UAV-mounted camera [15].

3 Applications

3.1 Enhancing Communication

In an era marked by a growing appreciation for remote communication, the increasing necessity for a sense of presence in interactions becomes indispensable to foster effective cooperation. We found four papers that assess an application designed to improve virtual collaboration.

In "GazeChat: Enhancing Virtual Conferences with Gaze-aware 3D Photos", He et al., propose a communication system that enhances the feeling of presence and conversation structure understanding by using a single webcam to represent a user's 3D profile photo [14]. Furthermore, in the paper titled "DynamiCross: Dynamic Representation and Sharing of Information with Flexible Cross-Reality Interactions", dynamic information sharing in a cross reality environment is explored using personal and shared objects in multiple display environments by turning large displays into multi-layered ones with AR [18]. In the study by Reilly et al., enhanced collaboration is examined by studying how the layout of a project room and the tasks performed affect the cognitive maps of virtual environments linked in mixed presence [29]. XRTeleBridge uses a 2D webcam view in the VR environment to optimize the viewing experience of individuals relying on a 2D screen in a conference call [31]. In another paper, users can navigate a virtual world using tangibles on a tabletop and large upright screen projections [40]. Lastly, "Interactable Topographical Map with Remote Cross Reality Collaboration Support" studies cooperation that is useful in firefighting or search and rescue through a 3D GPS-based map for guiding journeys in undeveloped terrains [7].

3.2 Adaptive Environment and Visualization Systems

Four research papers investigate how immersive technologies can be leveraged to create responsive, user-centric environments and visualize complex data or scenarios, enhancing user interaction, comprehension, and overall experience in diverse fields.

SelectVisAR, a system for selectively visualizing virtual environments in AR to prevent information overload, shows that selective visualizations do not significantly impact event identification, but smaller visualizations risk task disconnection and that users preferred static over dynamic visualizations [8]. Quest - UbiquX, a location-based game, explores a MR tabletop interface with collaborative multi-player phases [43]. The paper titled "Towards Responsive Architecture that Mediates Place: Recommendations on How and When an Autonomously Moving Robotic Wall Should Adapt a Spatial Layout" explores responsive architecture, focusing on how autonomous spatial adaptation, aided by robotically moving walls, fosters a sense of place. In this article, the balance of spatial, situational, and subjective qualities is key to meaningful spatial adaptation [23]. "CRVideo: Cross-reality 360° Video Social Systems Exploration" examines a cross reality 360° video social system designed to cater to varied user personalities. In this study, the transitions between virtuality and physicality levels are explored to address the distinct social habits of extroverted and introverted users [41].

3.3 Across Industries

This section presents applied research papers that we found in the Architecture, Engineering, and Construction (AEC) industry, the reservoir engineering industry, and the archaeology industry.

"Enhancing Reservoir Engineering Workflows with Augmented and Virtual Reality" presents an XR-based application for reservoir engineering workflows, enabling intuitive visualization, analysis, and multi-user collaboration on complex reservoir models, paving the way for enhanced scientific data analysis in various domains [5]. A study suggesting a roadmap for XR implementation in the AEC industry explores the integration of Building Information Modeling (BIM) and the potential for enhancing collaboration, design, and project management [2]. Magalhaes et al. propose an information system for an adaptive MR system that integrates virtual reconstructions of archaeological sites with the real environment [21].

3.4 Education & Training

XR's ability to harness and provide information to a user by use of immersive experiences enables a deeper conceptual understanding of a subject matter to keep the user engaged. Frameworks and innovative approaches to collaborative XR for education and training are presented in this section.

In the world of construction and industrial applications, "Cross-platform Virtual Reality for Real-time Construction Safety Training Using Immersive Web and Industry Foundation Classes" proposes a cross-platform VR framework, CPVR, for safety training in the construction industry, accessible via mobile devices or desktops to assess employees' safety knowledge, and a method for creating 3D visuals of Building Information Modeling (BIM) models for collaborative environment planning [4]. For a process to integrate industrial assets into an immersive environment, "Streamlining XR Technology Into Industrial Training and Maintenance Processes" discusses the development of such a process for enhanced decision-making in manufacturing [35]. Furthermore, Back et al.'s paper mirrors a real-world factory into a "virtual factory" to investigate the use of virtual, mobile, and MR for control and collaboration in a factory [3].

In the field of higher education, "Model Augmented Reality Curriculum" offers a framework for teaching AR in universities that is aligned with industry needs and provides insights into its integration into academic fields [10]. For laboratories, May explores the benefits and limitations of the use of online laboratories as cross reality spaces in engineering education, particularly for international students [22]. In addition, O'dwyer et al.'s paper on volumetric video for museological narratives explores AR and humor for cultural heritage applications. The research affirms that playful storytelling enriches visitor experiences [24]. Lastly, in "CourseExpo: An Immersive Collaborative Learning Ecosystem", the authors introduce a remote learning ecosystem where learners' avatars interact, learn, and discover in a common virtual space. The research focuses on facilitating and assessing content knowledge, engaging learners via immersion and community building, and creating support for facilitators [20].

3.5 Medicine

The use of XR technologies also has applications in the field of medicine for collaboration. Through immersive simulations, real-time visualization, and interactive learning environments, XR technologies enable innovative approaches to medical training, patient care, and diagnostic procedures, thus contributing to advancements in medical education and healthcare delivery. For instance, the paper "Anatomy Studio II, a Cross-Reality Application Using AR and VR to Teach Virtual Anatomy at Universities" enables real-time collaborative dissections with interactive features, enhancing resource efficiency and learning outcomes. Despite challenges, the paper presents opportunities for future research in digital anatomy education [19]. On the other hand, Chen et al. emphasize the need for personalized cross reality applications in the context of training and rehabilitation for older adults, arguing against a one-size-fits-all approach due to the diversity of this user group. The authors propose a generic architecture for personalized cross reality applications and stress the importance of adaptability and individualization [6]. Further, Guarese et al.'s study introduces an asymmetric AR/VR system for blind or visually impaired individuals by leveraging remote-sighted guidance and effective audio interfaces to improve navigation [13].

4 Discussion & Future Directions

In this paper, we briefly summarize the current literature on cross reality and collaboration. Our research explores various facets of XR collaboration. Nonetheless, these explorations further unearth multiple opportunities for future investigation.

4.1 Shared Physical Spaces and Technology Disparities

The introduction of XR devices in new environments undoubtedly introduces new dynamics in the way individuals relate to each other. Developments in XR communication enhancement attempt to increase the feeling of presence by fostering increased levels of immersion and representations of people. Future research should focus on individuals in proximity to users immersed in XR technology. Exploring ways to enhance the experience of non-adopters in the presence of XR technology might expand the wider acceptance of XR for collaboration. Such research should study the factors that lead participants to believe that XR technology disrupts intimacy. Possible examples might explore software and hardware designs of head-mounted displays (HMD) that communicate to the surrounding people that they are seen and heard. One way to achieve this is through multimodal interaction. Furthermore, improving communication with other users in the same room while wearing an HMD would play a significant role in XR collaboration. A future direction for XR collaboration could include external displays attached to HMDs, 2D monitors in the physical room for communication with other users, auditory feedback to increase user experience, and novel ways to reduce cognitive load during VR/AR/MR collaboration, as part of the HUI research.

4.2 Privacy Concerns and Consent Overload

The concerns surrounding data privacy and the overload of consent requests in XR collaborations present a delicate balance to be achieved. While the existing literature emphasizes the importance of consent, the research pinpoints the need to avert the risk of overloading users with requests [1], which could degrade the XR experience. Future work should explore the principles of 'Privacy by Design' to ensure data minimization and privacy protection from the outset of system design. Consent mechanisms that are not intrusive yet transparent would be valuable areas of exploration. Exploring varying modes of communication for acquiring consent, such as a pop-up notification, an auditory bell, a voice assistant, a virtual embodiment of a smart assistant, a haptic notification, the sudden appearance of a virtual object, using everyday objects as a stimulus, or combinations of the above, could shed light on which method is suitable for different scenarios. As XR technologies continue to mature and permeate various aspects of our lives, the need for research focusing on responsible and equitable use becomes increasingly crucial.

4.3 Improving Collaborative XR Application Technology

The rapid development of web-based collaborative XR applications has presented novel opportunities and challenges. Web-based apps for XR offer unparalleled accessibility, enabling users to access immersive experiences from any device with a modern web browser, thus simplifying adoption, and facilitating collaboration across diverse platforms. Although an increase in web-based collaborative applications would also increase XR technology adoption, the issue of latency in such applications, especially in contexts requiring precise coordination, poses a significant barrier. Team-based competitive sports or physically active groups (e.g., dancers), would benefit from real-time coordination and open up the possibility of remote training and group practice for professionals. The confluence of XR with other emerging technologies, such as artificial intelligence and 5G, provides fertile ground for innovation. Future work should focus on the optimization and improvement of network architecture and data compression techniques to ensure the real-time interaction capabilities of these applications. Research could explore multi-access edge computing (MEC) for XR collaboration to reduce latency and process data closer between users. Such improvements can open up the potential of AI inferences in immersive XR to analyze real-time data streaming of sensor data from other XR users in the network.

4.4 Designing for the User

In the realm of XR, it is crucial to comprehend users' cognitive behaviors and cater to their needs in order to improve their overall experience and promote wide adoption. Motion sickness is a common issue in XR experiences, particularly with head-mounted displays (HMDs). Investigating the causes of motion sickness and developing prevention techniques can significantly increase user comfort. The overall feeling of presence can thus be improved through the exploration of novel methods of locomotion, visual design, and sensory feedback in order to reduce motion sickness. This issue becomes significantly important when the user crosses between realities. We expect to see more papers in the future that aim to mitigate motion sickness while the user transitions from one reality to another.

Additionally, taking a user-centric approach when developing XR applications requires careful consideration of individual skills, preferences, and limitations. Customizability and adaptability should be at the heart of XR design, letting users personalize their experiences to their specific requirements. Important data can be acquired by studying the effects of various input modalities and interaction styles on diverse user profiles.

Another critical area of focus in XR design is spatial navigation. Further research can be conducted on the effectiveness of different spatial mapping techniques, wayfinding cues, and user interfaces to optimize navigation within virtual spaces between different realities. All in all, by gaining insights into these areas of XR design, developers can create applications and experiences that minimize adverse effects on the overall user experience.

4.5 Hybrid User Interfaces

In cross reality, users expect a seamless transition between different realities. HUIs focus on the concurrent use of multiple devices to complement each other, optimizing technology for specific tasks within a cohesive interface, i.e., a combination of heterogeneous displays and interaction device technologies [9]. The connection between cross reality and HUIs is especially evident when examining software architectures that function across devices, ensuring hardware interface continuity, and unique applications that utilize multiple XR interfaces for collaboration.

Interface continuity is crucial for cross reality technologies. Users might favor specific devices or tools across realities due to their ergonomics or functionality. For example, a controller appreciated in AR might be desired in VR. Smooth device interoperability across realities can increase user comfort and efficiency.

HUIs offer a promising potential for collaborative cross reality applications. For instance, the "Mobile Displays for Cross-Reality Interactions between Virtual and Physical Realities" article identifies VR and Physical Reality users as distinct groups [34], and highlights that there is a scope to explore unified interfaces where users employ haptic mobile displays in XR, such as with an HMD.

5 Conclusion

In this paper, we summarize the current state of research on cross reality for collaboration. After reviewing four databases, we provide an overview of existing approaches and identify areas for future research, such as non-adopters in the presence of XR technology, 'Privacy by Design' principles, and improvements in reducing latency for collaborative activities, while highlighting the relationship between cross reality and hybrid user interfaces. We hope that our paper can guide future researchers, engineers, and developers to create superior infrastructures and applications for cross reality collaboration.

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