DOT/FAA/AM-24/12

Office of Aerospace Medicine

Washington, D.C. 20591

A Qualitative Review of Extended Reality-Enabled Remote Collaboration: Human Factors Considerations and Implications for NAS Maintenance Practices

Brett Torrence[1, 2]
Justin Durham[3]
Rebecca DiDomenica[3]
Inchul Choi[3]
Braden Tanner[1]

[1]Civil Aerospace Medical Institute (CAMI)
Federal Aviation Administration
Oklahoma City, OK 73169

[2]Veterans Health Administration
U.S. Department of Veterans Affairs

[3]Cherokee Nation 3S, LLC
Oklahoma City, OK 73169

June 2023

Technical Report

NOTICE

This publication and all Office of Aerospace Medicine technical reports are available in full text from the Civil Aerospace Medical Institute's publications website (www.faa.gov/go/oamtechreports) and at the National Transportation Library's Repository & Open Science Access Portal (https://rosap.ntl.bts.gov).

Technical Report Documentation

1. Report No.	2. Title & Subtitle		
DOT/FAA/AM-24/12	A Qualitative Review of Extended Reality-Enabled Remote Collaboration: Human Factors Considerations and Implications for NAS Maintenance Practices		
3. Report Date June 2023			4. Performing Organization Code Click or tap here to enter text.
5. Author(s) B. Torrence, J. Durham, R. DiDomenica, I. Choi, B. Tanner			6. Performing Org Report Number Click or tap here to enter text.
7. Performing Organization Name & Address Civil Aerospace Medical Institute (CAMI), FAA Oklahoma City, OK 73169			8. Contract or Grant Number Click or tap here to enter text.
9. Sponsoring Agency Name & Address Office of Aerospace Medicine, Federal Aviation Administration, 800 Independence Ave., S.W., Washington, DC 20591			10. Type of Report & Period Covered Technical Report
11. Supplementary Notes Click or tap here to enter text.			

12. Abstract

Remote collaboration is a virtual maintenance support strategy that allows local technicians to virtually engage with remote experts anywhere at the time of need to receive procedural guidance and instruction. Remote collaboration could enable virtual maintenance strategies (remote assistance, virtual inspection, site surveys, and training) for the FAA's Technical Operations organization and help optimize resources, such as travel costs and the time of local and remote workers. While audio and teleconferencing technologies have been found useful for remote collaboration, these traditional methods limit the way in which physically distanced teammates communicate and may not accurately reflect the collaborative behaviors that would occur in face-to-face maintenance environments. Extended reality (XR) technologies, such as augmented reality (AR), mixed reality (MR), and virtual reality (VR), can enhance the capabilities of collaborators through advanced visualization features and a shared visual perspective to improve the quality and efficiency of maintenance work. To understand how XR can support remote collaboration processes for maintenance, we conducted a literature on XR-enabled remote collaboration research. We identified 74 articles and reviewed each article to understand trends in the following areas: (a) device types of local and remote users, (b) interaction modes between local and remote users, (c) remote collaboration metrics, and (d) human factors issues and considerations. Findings from the literature and the implications of these results for future human factors studies and field evaluation work in Technical Operations are discussed.

13. Key Words		14. Distribution Statement
Remote collaboration, remote assist, maintenance, extended reality, augmented reality, mixed reality, virtual reality, human factors		Document is available to the public through the National Transportation Library: http://www.faa.gov/go/oamtechreports/
15. Security Classification (of this report) Unclassified	16. Security Classification (of this page) Unclassified	17. No. of Pages 41

Acknowledgements

This research was conducted under the Air Traffic Program Directive/Level of Effort Agreement between the Human Factors Division (ANG-C1), FAA Headquarters, and the Aerospace Human Factors Research Division (AAM-500) at the Civil Aerospace Medical Institute (CAMI).

Table of Contents

List of Figures

List of Abbreviations

3D	Three-Dimensional
AR	Augmented Reality
BIM	Building Information Modeling
BNS	Behavioral Navigation System
CAD	Computer Aided Design
CAVE	Cave Automatic Virtual Environment
DTIC	Defense Technical Information Center
FAA	Federal Aviation Administration
HHD	Handheld Device
HMD	Head-Mounted Display
MR	Mixed Reality
NAS	National Airspace System
NASA-TLX	NASA Task Load Index Questionnaire
NTRS	NASA Technical Reports Server
PI	Principal Investigator
PPE	Personal Protective Equipment
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SME	Subject Matter Expert
SUS	System Usability Scale
VR	Virtual Reality
XR	Extended Reality

Abstract

Remote collaboration is a virtual maintenance support strategy that allows local technicians to virtually engage with remote experts anywhere at the time of need to receive procedural guidance and instruction. Remote collaboration could enable virtual maintenance strategies (remote assistance, virtual inspection, site surveys, and training) for the FAA's Technical Operations organization and help optimize resources, such as travel costs and the time of local and remote workers. While audio and teleconferencing technologies have been found useful for remote collaboration, these traditional methods limit the way in which physically distanced teammates communicate and may not accurately reflect the collaborative behaviors that would occur in face-to-face maintenance environments. Extended reality (XR) technologies, such as augmented reality (AR), mixed reality (MR), and virtual reality (VR), can enhance the capabilities of collaborators through advanced visualization features and a shared visual perspective to improve the quality and efficiency of maintenance work. To understand how XR can support remote collaboration processes for maintenance, we conducted a literature on XR-enabled remote collaboration research. We identified 74 articles and reviewed each article to understand trends in the following areas: (a) device types of local and remote users, (b) interaction modes between local and remote users, (c) remote collaboration metrics, and (d) human factors issues and considerations. Findings from the literature and the implications of these results for future human factors studies and field evaluation work in Technical Operations are discussed.

Keywords: remote collaboration, remote assist, maintenance, extended reality, augmented reality, mixed reality, virtual reality, human factors,

Introduction

The Federal Aviation Administration's (FAA's) Technical Operations maintains the infrastructure of the National Airspace System (NAS) and is responsible for the installation, maintenance, certification, and modification of facilities, systems, and equipment. The Technical Operations organization performs a range of mission critical tasks including, but not limited to, preventative and corrective maintenance on air navigation systems, site inspections and condition assessments, and design, construction, and modernization of NAS facilities. The changing landscape of the NAS requires a broader set of technical expertise and technical data for effective performance. Technicians, for instance, may be required to maintain and certify different systems (e.g., navigation aids, automation systems, radars), as well as possess the technical proficiencies to maintain new and legacy infrastructure. The use of innovative technologies, such as extended reality (XR) and virtualization, can support the increasing demands placed on the workforce and enable new maintenance strategies to support operational effectiveness.

XR is an emerging solution in aviation, particularly for maintenance support strategies, because of the increased accessibility of this technology in headset, tablet, and wearable forms (Torrence & Dressel, 2022). XR is an umbrella term describing immersive technologies that combine real world and virtual objects in a single environment, and the interactions that occur between humans and technology (Alizadehsalehi et al., 2020). XR, which encompasses augmented reality (AR), mixed reality (MR), and virtual reality (VR), has the potential to present users with an immersive and data-rich environment to support task performance. XR devices can digitally give users the right information at the right time, reduce the need for subject matter experts (SMEs) to be onsite, and enable more effective communication and collaboration between physically distanced teammates (Key et al., 2022; Y. Lee & Yoo, 2021; P. Wang, Bai, Billinghurst, Zhang, He, et al., 2020).

One common application of XR in maintenance is remote collaboration. Remote collaboration is the process of two or more physically distributed individuals working interdependently toward a common goal (Marques, Silva, Alves, et al., 2022). In maintenance settings, remote collaboration typically involves a local user, who is performing an onsite task, and a remote user, who is serving as the technical expert or instructor providing guidance, coaching, or training. Traditional remote collaboration has been limited to audio and/or video streaming to convey the local user's point of view and the remote user's guidance and instructions. However, these traditional methods limit the ability of collaborators to gather information as they would if collaborating in a co-located space – that is, through conversations and gestures, actions with the physical workspace, and a shared workspace environment (Ens et al., 2019; Tait & Billinghusrt, 2015).

XR-enabled tools have the potential to improve remote collaboration by expanding non-verbal communications via hand gestures, eye gaze, and haptic feedback; allowing users to superimpose digital information onto the real world; and improving feelings of co-presence between users (Marques, Silva, Teixeira, et al., 2022; P. Wang et al., 2023). These features can better mirror in-person collaboration, enable collaboration abilities not possible in real life such as sharing a single point of view (Le Chénéchal et al., 2019), and support knowledge sharing across collaborators when additional know-how is needed onsite.

XR-enabled remote collaboration has received substantial research attention because of its expected benefits for maintenance practices (e.g., De Pace et al., 2019; Le Chénéchal et al., 2019; Vorraber et al., 2020; Zhu et al., 2022). Still, rapid advancements in XR typically result in research focusing predominantly on technological innovations, and less so on the human factors that shape effective collaboration (Ens et al., 2019). Some recent work (e.g., Marques, Teixeira, et al., 2022) focuses on understanding the aspects of XR that support collaborative processes and behaviors, but critical questions remain. For instance, what XR devices and capabilities best support the unique role requirements of the local and remote user? How does XR improve communication and knowledge sharing? What type of collaboration structure is most effective for maintenance tasks? What human factors issues are improved and/or worsened by the use of XR?

XR has the potential to support maintenance practices, improve maintenance work in terms of quality and efficiency, and enable more resource-efficient strategies in terms of time, cost, and personnel. As the demands of NAS maintenance increase, it is essential to understand how AR, MR, and VR can be appropriately used to support maintenance strategies, minimize human factors issues, and maintain the safety of maintenance personnel. The purpose of this report is to present a systematic review of the research literature on XR-enabled remote collaboration. This report offers a comprehensive look at the use of remote collaboration within maintenance (and related) domains, common XR devices used by local and remote users, maintenance tasks supported by remote collaboration, benefits of using XR over traditional methods, and human factors considerations for the use of these technologies. This report will inform joint human factors studies and field evaluation efforts on remote collaboration for NAS maintenance.

Extended Reality

XR is an umbrella term used to describe different types of immersive technologies – including AR, MR, and VR – that combine aspects of the physical and virtual world. The term “XR” encompasses all reality-enhancing technologies, with AR, MR, and VR being specific technologies aimed at extending human performance capabilities and experiences.

The technologies differ in the extent to which they blend reality with the virtual world and/or obscure the physical environment from the user (Milgram & Kishino, 1994). AR augments physical environments by superimposing digital information on the user’s visual field so that virtual and real-world content can be viewed together (Z. Wang et al., 2021). With AR, there is some real-time interaction between virtual and physical objects, but the interactions tend to be more superficial than in MR environments. MR, like AR, combines virtual and real-world objects into a single display, thus many consider MR to be an extension of AR. However, unlike AR, MR uses technology such as spatial reference, spatial audio, and three-dimensional (3D) data to enable more real-time interaction with the virtual environment and objects. Consequently, a common distinction between AR and MR is that MR systems possess some “knowledge” about the real world, whereas AR systems do not (Skarbez et al., 2021). VR, on the other hand, fully immerses users in a computer-generated virtual environment (Kaplan et al., 2021). VR is an entirely artificial environment that is characterized by the feelings of immersion and presence – that is, the extent to which the environment reproduces a sense of realism and the feeling of “being there” (Brown, 2018). VR systems typically offer users a high degree of interactivity with virtual objects through body, head, and hand tracking.

Device Types

The display devices used to convey AR, MR, and VR experiences have expanded in type and form factor as technological capabilities have advanced. Users experience XR through head-mounted displays (HMDs), wearable computer glasses (i.e., smart glasses), projectors, hand-held devices (e.g., smartphone, tablet), controllers, haptic gloves, and spatial audio, among others. AR displays primarily include hand-held mobile devices and HMDs, such as Microsoft HoloLens, Magic Leap, and RealWear Navigator. Wearable AR headsets inherently offer passthrough, or see-through, capabilities which allow users to view the real world while wearing the device. AR HMDs come in monocular (i.e., one eye) or binocular (i.e., two eye) options. The former is believed to minimize hardware interference during task performance, whereas the latter produces a more natural visual experience for the user (Newton, 2022).

MR displays primarily use passthrough HMDs and immersive HMDs (Catbas et al., 2022). Passthrough HMDs that offer MR experiences are similar to those used for AR, such as Microsoft HoloLens and Magic Leap, in that they allow users to view virtual and physical objects simultaneously. Immersive HMDs, such as the HTC Vive XR Elite and HP Reverb G2, obscure a user's view of the real world, but offer the option for viewing the outside world through integrated cameras in the HMD. For VR, HMDs are the primary device type used to immerse users in a virtual environment, but VR experiences are also sometimes achieved using projections. For example, the cave automatic virtual environment (CAVE) projects images on the walls of a room. Commonly used VR HMDs include the Varjo Aero, Varjo VR-3, Meta Quest 2, and HTC Vive Pro. VR systems can be standalone – such that all of the equipment needed for the HMD to run is contained in the headset (for example, inside-out tracking) – or tethered, which requires a wired computer connection and external cameras.

The type of information, interactions, and experiences available to users is bounded by the AR, MR, or VR device type. Hand-held AR devices, such as smartphones or tablets, can capture the task space and augment the user's view by superimposing annotations onto the device's screen. However, handheld devices (HHDs) do not enable hands-free operations, which may be essential if users need to view the display while manipulating a piece of equipment. HHDs may require users to split attention between the task and device display, leading to greater strain on attention.

Wearable AR and MR devices, in the form of computer glasses or HMDs, typically do not occupy a user's hands, leaving them free to perform hands-on activities while maintaining view of the task space, which may be more critical in dynamic task settings (Johnson et al., 2015). However, some HMDs require the use of a controller for interacting with virtual objects. In addition, HMDs may be tiring to wear, limit one's field of view, and not fit with required attire, such as Personal Protective Equipment [PPE]).

VR systems generate experiences that are not suitable for individuals working with equipment onsite. However, immersing remote users in a virtual replica of the local workspace may offer an effective shared environment for collaboration (P. Wang et al., 2019). XR device displays and recent advances in sensory and interaction capabilities (e.g., eye gazes, hand gesture, haptic feedback; Bai et al., 2020; Cho et al., 2022; Jebbar et al., 2019; van Oosterhout et al., 2015) have the potential to support realistic collaboration experiences if aligned appropriately with task requirements.

Remote Collaboration

The modernization of the NAS calls for a broader range of technical expertise and information to maintain and sustain critical facilities, systems, and infrastructure. However, the needed expertise or guidance may not always be available nearby. This increase in complexity of the NAS increases the need for a collaborative approach to maintenance tasks such as field support, site surveys, inspections, and training. With the collaborative maintenance approach, tasks are completed collaboratively between a team member local to the designated facility and a geographically distanced (or remote) team member serving as a technical expert. In such situations, the local technician shares visual and/or verbal information with the remote expert, who offers step-by-step guidance or coaching until assistance is no longer required (Calandra et al., 2021). The remote collaboration process can help users overcome the challenge of resource constraints and distance and ensure that the right expertise is available at the right time (and in the right format).

Remote collaboration, also referred to as remote expert assistance or collaborative maintenance, is defined as a "multi-stage and iterative process going through steps such as sharing and perception of collaborative state, users interacting with the system to express collaboration intent, and manipulating physical subjects, etc." (P. Wang, Bai, Billinghurst, Zhang, Zhang, et al., 2021, para. 2). The idea of remote collaboration has origins in Computer-Supported Cooperative Work, which seeks to understand how technology can support collaboration, communication, and knowledge sharing between physically distributed individuals (Y. Lee & Yoo, 2021; Marques, Silva, Alves, et al., 2022). In P. Wang, Bai, Billinghurst, Zhang, Zhang, et al. (2021), remote collaboration is described as a "human-centered technical activity" (para. 2) that enables collaborators to understand their partner's intention and perspective and work together despite geographic restrictions to achieve a common goal.

Remote collaboration in maintenance is unique from other forms of remote collaboration because it is an asymmetrical process. Specifically, the distribution of knowledge between users is not balanced (P. Wang, Bai, Billinghurst, Zhang, Zhang, et al., 2021). Local users understand the physical workspace and local problem, whereas the remote expert has the technical knowledge for completing the task (P. Wang, Bai, Billinghurst, Zhang, He, et al., 2020). The dispersed information across collaborators makes proper communication critical to achieve effective coordination, as the local user must comprehend and carry out the instructions of the expert, and the expert must properly guide the local technician in a safe and efficient manner. The media and methods used for remote collaboration are therefore critical for establishing common ground and a shared understanding between the local and remote individuals.

Traditional Approaches to Remote Collaboration

Audio and video are traditional media for remote collaboration, with video streaming being the most common solution (K. Kim et al., 2018). In an audio-only scenario, local and remote users communicate via telephone and are limited to verbal descriptions of the problem, needs, and guidance. In video-conferencing scenarios, local users share live video of the task space from a fixed-view camera to give the remote expert a view of the workspace, allowing both verbal and visual communication of the problem. This shared visual space increases situation awareness – a shared understanding of the task in relation to the end goal. It also offers a conversational grounding of the task state to help ensure mutual understanding and assumptions between collaborators (Fussell et al., 2003).

Research generally suggests that audio and videoconferencing benefit the remote collaboration process for physical tasks, in terms of communication and performance (Fussell et al., 2004). However, traditional methods limit the way in which users communicate with one another, offer only a subset of potential communication cues, and do not mimic the same type of collaboration that would occur if collaborators were co-located. For instance, remote experts are typically restricted to passive viewing of the visual feed and limited in their use of non-verbal communication cues (Calandra et al., 2021; Marques, Silva, Alves, et al., 2022). Other identified limitations include the visual field being fixed to the local user, poor field of view for the remote expert, the inability to reference areas of interest, and increased workload for local users who have to physically perform the task while listening to verbal instructions (Tait & Billinghurst, 2015; P. Wang, Bai, Billinghurst, Zhang, Han, et al., 2020; P. Wang, Bai, Billinghurst, Zhang, He, et al., 2020). While these methods permit remote collaboration, they may not fully enable the type of collaboration, communication, and actions needed when working on safety-critical equipment.

Extended-Reality Remote Collaboration

The asymmetrical nature of collaborative maintenance tasks stresses the need for proper communication and coordination. Without these components, remote experts may be unable to transfer knowledge effectively to the local technician. Huang et al. (2018) note that the loss of common ground and mutual understanding between collaborators is a main contributor to remote collaboration inefficiencies. Given that traditional approaches to remote collaboration (e.g., audio or video-based collaboration involving reduced non-verbal cues and limited visual information) constrain the interaction between local and remote users, many have turned to XR-enabled solutions as a potential answer for remote collaboration (P. Wang, Bai, Billinghurst, Zhang, Zhang, et al., 2021). XR-enabled remote collaboration includes collaborating across AR/MR devices, between AR/MR and VR devices, and between AR/MR devices and traditional methods (Y. Lee & Yoo, 2021).

XR is a proposed remedy to the drawbacks of traditional approaches because of its potential to support more natural and intuitive interactions. The suggested benefits of AR, MR, and VR technologies for remote collaboration are the sharing of non-verbal cues (e.g., eye gaze, gestures; Bai et al., 2020), AR annotations (e.g., digital markers, drawing; Ludwig et al., 2021; P. Wang, Bai, Billinghurst, Zhang, He, et al., 2020; Marques, Silva, Rocha, et al., 2021; Mizuno et al., 2021), user-friendly interfaces (De Pace et al., 2019), and improved viewing like the *see-what-I-see* perspective, and depth perception of the local workspace (Anton et al., 2018). These benefits are important for maintenance tasks where physical actions and other non-verbal communication cues often complement an expert's verbal instructions. In addition, the display interfaces of AR/MR devices offer simple, clear annotations that help focus user attention on task needs (Marques, Ferreira, et al., 2022). XR supports *synchronous* and *asynchronous* collaboration paradigms (Calandra et al., 2021). In synchronous settings, the remote expert works simultaneously with the local user as the task is completed. In asynchronous settings, the remote expert delivers the needed information via AR/MR content to the local user, who completes the task without the expert online.

Potential NAS Maintenance Applications

For Technical Operations, XR-enabled remote collaboration has the potential to inform the following practices: remote assistance, virtual inspections, site surveys, and training. For remote assistance, a remotely located expert offers procedural guidance, coaching, and assistance to a local technician for maintenance/troubleshooting/system support. Remote assistance provides the local technician, who may not have the technical expertise or information needed to complete the task, real-time assistance. XR devices present collaborators with a shared visual space by allowing the remote expert to see what the local technician is looking at and enable verbal and non-verbal communication cues for effective procedural guidance.

XR can enable *virtual visits* to support site survey and visual inspection practices, as well as improve human visual capabilities that typically hinder inspection tasks. In such situations, the onsite technician could *transport* the remote expert(s) to the local facility through a mobile device or HMD providing a *'see-what-I-see'* point of view. The expert could then offer remote assistance or coaching as the local user walks through the NAS facility to perform conditions assessments or equipment implementation strategies. Additionally, the enhanced visualization features of AR/MR systems would allow critical information, such as as-planned, digital models, to be viewed simultaneously with the as-is condition (Halder et al., 2022; Runji & Lin, 2019). XR devices can enable asynchronous visits as well by capturing imagery of equipment and infrastructure, which can be stored and analyzed at a later point (and potentially recreated into a 3D model that is viewable in VR).

XR-enabled remote collaboration can also enhance on-the-job training (OJT) and familiarization practices. The remote user (i.e., instructor) could connect with the local user (i.e., trainee) to give procedural guidance and coaching on the designated task or learning objective. The instructor could see the trainee's point of view and supply verbal and non-verbal instructions to help develop job-relevant skills. These sessions could be conducted one-to-one or one-to-many (Marques, Silva, Dias, et al., 2022a). XR may not only make remote training possible, but potentially improve instruction and learning through advanced capabilities, such as haptic feedback, gesture-based instruction, eye tracking, and AR annotations. Importantly, remote collaboration for the purposes of training can serve as a distance learning strategy that reduces the need for trainees to travel and increases the availability of job critical training.

Methods

We conducted a systematic review of research on XR-enabled remote collaboration to document the current state of the field. We included studies investigating the use of AR, MR, and/or VR for remote expert assistance and remote collaboration applications in domains relevant to technical operations, including maintenance, engineering, construction, and aviation. We used seven databases to identify articles relevant to this topic – Defense Technical Information Center (DTIC), Embry Riddle Commons, Google Scholar, IEEE Xplore, JSTOR, NASA Technical Reports Server (NTRS), and Web of Science.

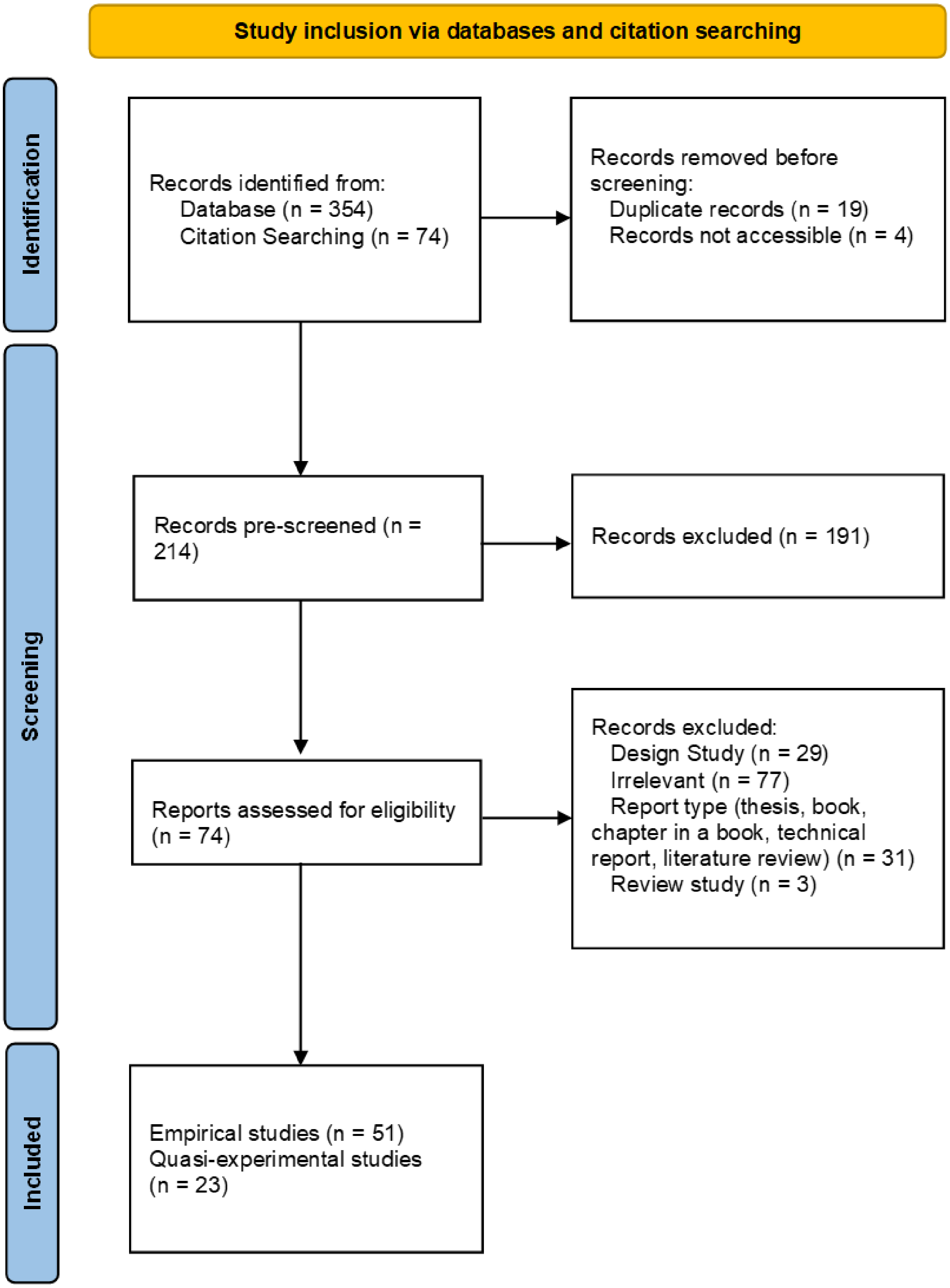
Each database was filtered for articles that included a combination of at least one domain phrase, at least one remote theme phrase, and a technology phrase. Domain phrases included "aviation," "construction," "engineering," and "maintenance." Remote theme phrases included "collaboration," "expert assistance," "guidance," "inspection," "knowledge transfer," "mentoring," "training," and "troubleshooting." Technology phrases included "AR," "XR," "MR," "VR," and "wearable computer glasses." We sourced additional articles from citation searches within FAA conference papers and Google Scholar[1] using the same keywords, or from the Principal Investigator (PI) directly. We reported these articles as "Citation Searching" during the article identification process. Figure 1 gives a visual representation of how we identified studies following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method.

The initial search yielded 428 identified articles. Of these, we excluded 23 articles because they were either not accessible, written in a foreign language, or duplicated. After reviewing titles and abstracts of the remaining articles, we excluded 191 articles that were outside of the topical scope of this review. We then screened the eligible articles with a full-text review. To meet final inclusion criteria, the articles were required to be peer reviewed and contain either empirical or quasi-experimental studies. This resulted in 74 studies to analyze for key variables.

[1] Initial literature searches were conducted with Google Scholar; the lack of an advanced search toolbar and a lack of a targeted topical area suggests the initial search results may be less targeted than the database searches.

Figure 1

Flow Diagram of Study Inclusion



We reviewed the main findings and methodology of each article and extracted information that aligned with the scope and focus of our effort. This information included:

- Task domain (e.g., aviation, construction, engineering, maintenance)
- Technology (e.g., AR, VR) and device type (e.g., HMD, mobile application) used by local and remote users
- Mode of interaction between local and remote users
- Performance metrics
- Human factors issues considered in the study[2]

Results

The articles included for analysis (N = 74) were published between 2000 and 2023. The majority (73%) were published between 2019 and 2023. The increasing number of publications in recent years reflects the increased availability of AR, MR, and VR technologies and the growing interest in using these technologies to enable remote collaboration and assistance for maintenance. Articles were sourced from *Frontiers in Robotics and AI, Frontiers in Virtual Reality, Human Factors, IEEE, International Journal of Human-Computer Interaction,* and *Safety Science,* among others. Fifty-one articles (69%) were empirical studies.

The application of XR-enabled remote collaboration and assistance was investigated across a range of tasks; namely, disassembly, assembly, replacement, inspection, installation, and training. A few articles illustrate the type of maintenance tasks being explored (e.g., Y. Lee & Yoo, 2021; Tea et al., 2022; P. Wang, Bai, Billinghurst, Zhang, Wei, et al., 2021). For example:

> Y. Lee and Yoo (2021) studied collaborative repair for a ball valve replacement involving disassembly, replacement, and assembly procedures. In this study, the local technician used an AR-supported tablet to display the local work environment to the remote expert who was wearing a VR HMD. The remote expert was able to convey the correct procedural actions needed to complete the ball valve replacement to the local technician's tablet via their actions with the VR system.
>
> Tea et al. (2021) compared an immersive VR system and non-immersive system for remote collaboration during a design review and building inspection task. In the immersive condition, team members reviewed the design drawings and interacted using VR HMDs, whereas those in the non-immersive condition reviewed the drawings and interacted using a desktop. Participants in the immersive remote collaboration system identified more design errors during the building inspection task than those in the non-immersive group.
>
> P. Wang, Bai, Billinghurst, Zhang, Wei, et al. (2021) explored the use of an MR remote collaboration system for an assembly training task. The authors compared a remote collaboration system that supported the sharing of three-dimensional (3D) computer

[2] These included: physical (e.g., motion sickness, visual fatigue, physiological fatigue), psychological (e.g., situation awareness, cognitive load), safety (e.g., limited field of vision, body positioning), environment (e.g., lighting, indoor vs. outdoor, interruption caused by PPE and tools, temperature), and usability (e.g., operation time, UI, interaction with systems) factors.

aided design (CAD) models to a system that supported 3D gesture and CAD model sharing for training on a water pump assembly task. The remote collaboration system that combined 3D gestures and CAD models showed benefits with respect to task completion time and user experience.[3]

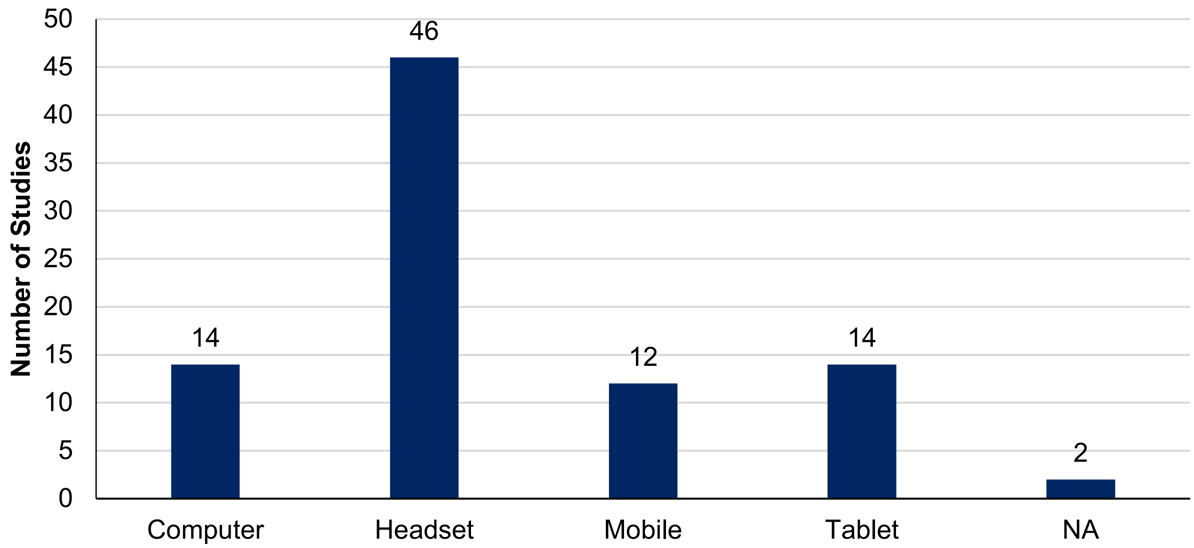
As demonstrated by these examples, XR-enabled remote collaboration has the potential to inform maintenance practices across many domains. The results below summarize the use of XR devices for local and remote users, the different modes of interaction enabled by XR, how the effectiveness of these technologies is typically measured in a remote collaboration paradigm, and different human factors considerations.

Local User – XR Type and Device Display

For local users, we summarized the prevalence of different XR types and device displays across the studies. The local user represents the on-site technician or individual located at the physical facility requiring support from the remotely located expert. Local users have access to the physical equipment to address problems. Local users are tasked with conveying information about the physical environment to the remote expert and following the instructions of the remote expert while receiving procedural guidance. In the majority of studies examined (62%), the local user used an AR-based device. VR-based devices were the second most common device (28%) followed by MR devices (10%). Figure 2 displays the prevalence of different device displays for local users. Headsets, or wearable computer glasses, were used in 52% of the studies. There was a roughly equal split among the remaining display types of interest: computers (16%), tablets (16%), and mobile applications (14%).

Figure 2

Prevalance of Device Displays for Local Users



[3] For additional examples of XR applications for maintenance training, see the following articles: Bailey et al. (2017); Bowling et al. (2008); Gangabissoon et al. (2020); Hoang et al. (2022); H. Lee et al. (2022); Li et al. (2022); Macchiarella and Vincenzi (2004); Rose et al. (2000); Valimont et al. (2007).

In maintenance environments, the use of headsets aligns well with common maintenance tasks, as it allows local users (technicians) to receive augmented/virtual information without occupying one's hands, enabling users to perform the tasks and receive instructions simultaneously. Following are examples of the use of headsets by local users:

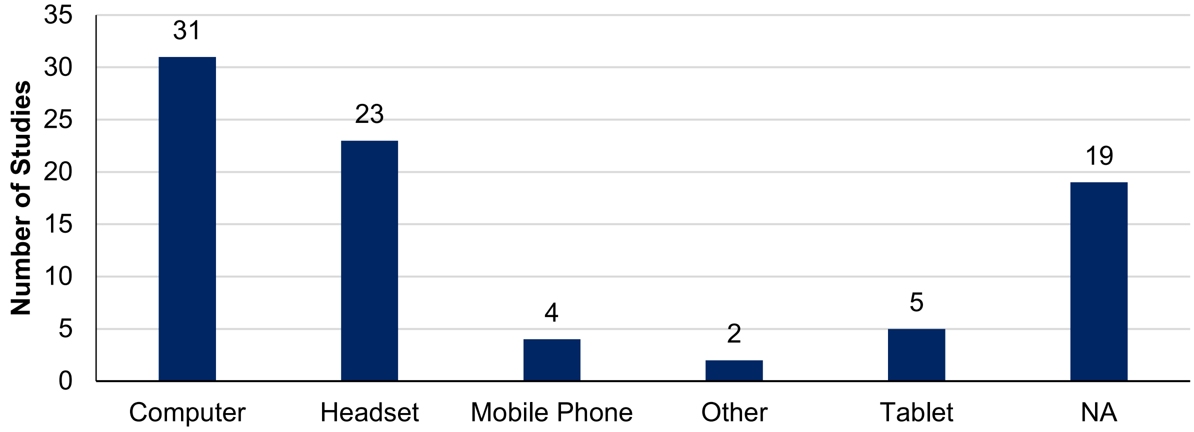
> In the study reported by Sara et al. (2022), maintenance workers were equipped with Vuzix® M400 Smart Glasses, a monocular video see-through display that allows for left or right eye use. The display is mounted on lensless frames and can be controlled by manual input or voice command.
>
> Sasikumar et al. (2019) examined the use of the Magic Leap device for local users in a remote collaboration setting. Magic Leap is a binocular headset that offers native passthrough capabilities, which allows the user to see the real world while wearing the device.
>
> The Magic Leap device allows users to interact with augmented information via a hand controller or gestures. Vorraber et al. (2020) evaluated the Microsoft HoloLens as a remote assistance tool on a sample of maintenance engineers. The Microsoft HoloLens is an optical HMD that supports hands-free operations, 3D-hologram information, and tracking.
>
> Conversly, Obermair et al. (2020) discussed the use of smartphone for remote collaboration for an assessmbly task. Local users held the smartphone device in front of the equipment to display video to the remote expert. During mechnical tasks like part handling, the smartphone was laid down.

Remote User – XR and Device Type

Similarly, we summarized the prevalence of different XR types and device displays used by remote experts across the selected studies. Remote users are physically distanced SMEs who have the required knowledge for addressing the maintenance issue but are less understanding of the physical workspace and local problem compared to the local user. Remote users must be able to adequately view the work environment in question and offer accurate and clear procedural guidance to the local user. In studies where the remote user used XR to communicate with the local user, 56% reported that the remote expert used a VR-based device, followed by AR-based devices (37%). Figure 3 displays the prevalence of different device displays used by remote users. The most used device display was a computer (47%) followed by headsets/HMDs (35%). Only a few studies reported remote experts using other devices, such as a tablet (8%), mobile phone (6%), or others (for example, an interactive table, 3%).

Figure 3

Prevalance of Device Displays for Remote Users



For remote experts to supply effective instruction and guidance, a clear view of the local workspace and the ability to communicate with the local technician are essential. Computers and HMDs appear to be commonly used device displays, as they enlarge the view of the shared visual field, thus enabling effective collaboration with the user. Several studies explore commonly used device displays. For example:

> Chen et al. (2019) studied remote collaboration for facility maintenance management, where the remote user connected via computer to the local user who was using a tablet device. The computer generated a shared visual field between the remote and local user and allowed for real-time interaction with the facility and equipment.
>
> Both G. Lee et al. (2018) and De Pace et al. (2019) investigated the use of a VR HMD, the Oculus Rift, for connecting remote experts to local users.
>
> In G. Lee et al. (2018), the use of the VR HMD allowed for both a shared *and* independent view of the local workspace, captured via the local user's AR headset and a mounted 360-degree camera. That is, the remote user could see what the local user was looking at, but also view the workspace independently from the local user. The HMD captured non-verbal communication cues of the remote user (e.g., hand gestures; G. Lee et al., 2018). De Pace et al.'s (2019) investigation of collaborative virtual environments in industrial maintenance involved remote experts using a VR HMD to assist a local user wearing an AR headset.

Mode of Interaction

The use of XR allows for interactions between local technicians and remote experts to extend beyond voice and video sharing. XR can enables communication, such as non-verbal cues, that are often relied on when collaborating on physical tasks in a co-located space. It can also enable communication that is only possible through advanced visualization capabilities, such as guiding virtual arms (Le Chénéchal et al., 2019). Understanding how XR allows communication via advanced visual information was a principal focus of several articles included in this review because of the importance of common ground, or shared knowledge and beliefs, to the remote collaboration process. The process of establishing common ground involves *conversational* *grounding*, which refers to the ways in which collaborators interact to ensure that messages are correctly understood and can include verbal and non-verbal behaviors (Fussell et al., 2003). Conversational grounding is a key aspect of the collaboration process as it enables local and remote users to coordinate activities and ensure messages are received as intended.

While the primary method of interaction still relies on the traditional modes of audio and video, several novel approaches to interaction, including AR annotations, hand gestures, eye gaze, and haptic feedback, were investigated as well. AR annotations are frequently used for enhancing communication between local and remote users. AR annotations, such as pins/markers, shapes, drawing, and pointing, are an effective way to recreate natural interactions and establish shared understanding between users. For example:

> Marques, Silva, Dias, et al. (2021) found that remote experts preferred using drawings (for example, circling the location of a component) and pre-defined shapes (such as arrows) to communicate with local users. Aligning AR annotations with the task environment resulted in shared awareness and better understanding of where to perform a subsequent action or task.

> Marques, Silva, Teixeria, et al. (2022) examined an AR-based annotation tool that allows both local users and remote experts to use annotations (e.g., drawing, pre-defined shapes), in addition to audio, to communicate about the maintenance procedure. Compared to an audio only communication, the use of the AR annotation tool not only resulted in quicker task completion time, but users thought the annotations made it easier to communicate, share ideas, understand information, and attend to the right information.

More novel approaches to interaction, including head tracking (Hatzipanayioti et al., 2019), haptic tools (Le et al., 2016), and hand gestures (Zentai-Henda et al., 2014), were also explored. For instance:

> Oyama et al. (2021) studied an XR behavioral navigation system (BNS) that superimposes the hand gestures of the remote expert over the hands of the local user (in their visual field) to enable remote expert guidance. The BNS was proposed to better support remote assistance as it allows the local user to directly follow the hand movements of the remote expert. Oyama et al. compared the BNS to a conventional remote assistance system (i.e., video sharing with AR annotations). The BNS resulted in faster task completion time and higher task success rate than the conventional approach. Additionally, both the remote experts and local users rated the BNS more favorably in terms of ease of use.

> Sasikumar et al. (2019) investigated the efficacy of user-centric and device-centric cues for communication. User-centric cues were defined as the eye gaze of the local user and the hand gestures of the remote expert, as they represent natural forms of non-verbal communication. Device-centric cues were defined as the view frustum of the local user (i.e., local user's field of view) and spatial annotations from the remote expert. Participants performed tasks while viewing the different cues. The authors found no significant difference between the cues in task completion time, feelings of co-presence, or attention allocation. Both remote and local users reported higher ratings of mental and physical effort when performing the task while viewing the user-centric cues, suggesting that these cues were more mentally and physically demanding. However, 60% (6 out of

10) of remote users preferred the device-centric cues, whereas 70% (7 out of 10) of local users preferred the user-centric cues.

P. Wang, Bai, Billinghurst, Zhang, Han, et al. (2020) explored the use of haptic (touch) feedback for hand-drawn cues during remote collaboration on an assembly task. Specifically, the authors studied whether providing remote experts with a tangible physical surface would support hand-drawn gestures compared to mid-air free drawing. Remote users sketched annotations on a physical surface or in the air using their hand, which were displayed in the local user's view. No significant differences in performance or number of operational errors were found across conditions. However, remote users preferred drawing on the tangible surface to the mid-air drawings. Remote users reported that the tangible surface offered better controllability of the drawings, making it easier to supply precise annotations to the local user.

Santos-Torres et al. (2022) examined how a local workspace is represented within the remote collaboration process and whether performance is impacted by the type of visual representation (e.g., shared experience, shared workspace). The shared experience scenario was a complete virtual replica of the entire task environment, including realistic avatars and office equipment/furniture. The shared workspace scenario only included the relevant workspace needed to complete the task. The authors found that the simple representation (i.e., the shared workspace scenario) was better in terms of task efficiency and workload than the complex representation (i.e., the shared experience scenario). This finding suggests that simple, task-oriented interfaces may improve collaboration.

Measuring the Effectiveness of Remote Collaboration

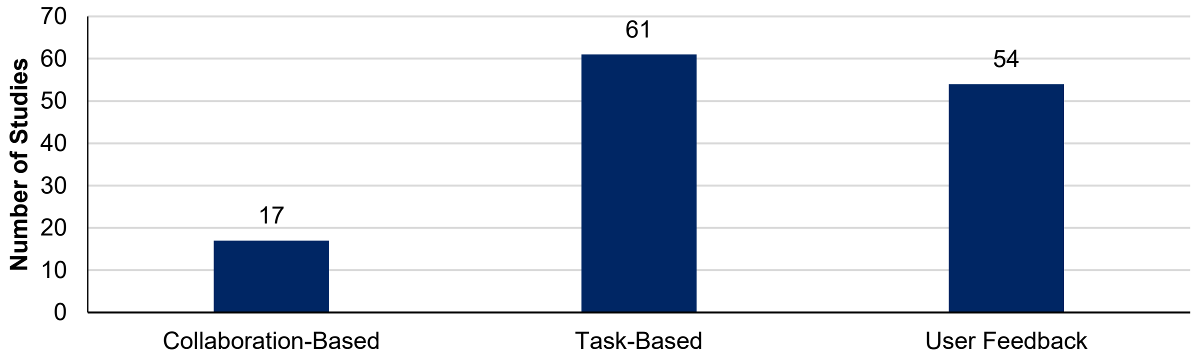
XR makes remote collaboration possible in ways not previously available to maintenance personnel. Besides enabling collaborative strategies, XR-enabled remote collaboration should show benefits for task performance. That is, it should reduce the time needed to perform the maintenance task, reduce workload, decrease errors, and promote better communication across remote and local users compared to traditional methods.

Performance metrics commonly used to evaluate XR-enabled remote collaboration can be categorized in three groups: 1) task-based, 2) collaboration-based, and 3) user feedback. The task-based category encompasses metrics that assess how well the task at hand was completed, including task completion time, error rate, number of correct steps, and workload. The collaboration-based category focuses on outcomes concerning the interaction and communication between the local and remote user. Collaboration-based metrics include number and types of interactions, visual clarity, number of words spoken, number of questions asked, and social presence (Harms & Biocca, 2004). User feedback represents user perceptions and reactions to the technology being used, including usability ratings, acceptability, and user friendliness. Figure 4 displays the prevalence of reported metrics across the identified studies.

Task-based measures, such as time on task and performance errors, were the most commonly used measures and were assessed in 82% of studies. User feedback measures were the second most common performance metric and were used in 73% of studies. Interestingly, collaboration-based measures, such as type of interactions and communication quality, were used least often as they were only used in 23% of studies. The emphasis of task-based measures and user feedback over collaboration-based metrics may reflect the need to establish basic performance benefits and acceptance in the early stages of this paradigm. That is, understanding if the technology produces equivalent or better performance than other alternatives and if users accept this technology might currently be more critical in establishing the efficacy of XR-enabled remote collaboration. However, in the long run, ensuring that this technology promotes effective communication and interaction may be just as important.

Figure 4

Prevalence of Performance Metrics Across Studies



Task-Based Metrics

Maintaining the services offered by systems and equipment relies on tasks being completed in an efficient, quality, and error-free manner. XR-based solutions should contribute to overall task performance and, ideally, reduce the workload or effort required to collaborate with a physically distanced teammate. Taken as a whole, evidence from the selected articles generally suggests that compared to traditional methods of collaboration (e.g., phone, video, and paper-based engagement), XR-enabled remote collaboration results in equivalent or better outcomes in terms of task completion time (e.g., Aschenbrenner et al., 2018; Asl & Dossick, 2022; Tavakkoli et al., 2020), number of errors (e.g., Braly et al., 2019, El Ammari & Hammad, 2019), and workload (e.g., Hou et al., 2013, Liu et al., 2022). Time spent on task was typically represented as the total time needed to complete a task (and sub-tasks) and errors were typically represented as the number of deviations from instructions or incorrect actions. Workload was frequently assessed using the NASA Task Load Index Questionnaire (NASA-TLX; Hart & Staveland, 1988)

For example, Obermair et al. (2020) compared an AR remote support system to traditional paper-based instructions for maintenance on an industrial PC. For the AR system, the local user connected with the remote expert by using a smartphone to capture the PC in real time. The remote expert could add virtual content to the smartphone display as well as deliver verbal instruction. While there was no difference in overall completion time, those using the AR-based system were quicker at identifying the correct PC type and removing the PC cover, whereas those using the paper-based instructions were quicker at removing and assembling the heat pipe. Importantly, those using the AR systems committed 75% less errors.

Del Amo et al. (2020) investigated an AR remote collaboration system involving local technicians and remote experts that used a structured-message format for improving remote diagnosis. The structured-message approach standardized communication between local technicians equipped with an MR HMD (i.e., HoloLens) and remote users equipped with a desktop computer. Specific message elements (e.g., equipment component, equipment location, required action) and AR content were generated based on the message (e.g., highlighting a component on the technician's visual field). The authors compared the AR approach to traditional communication methods (phone call and emails) on the remote diagnosis of an aircraft's fuel hatch. There was no difference in the number of errors between conditions, but the AR system reduced task time by 56%.

Marques, Silva, Dias, et al. (2022b) compared remote collaboration using an AR-based guidance system to traditional video chat for a maintenance task involving replacing components, plugging and unplugging energy modules, removing sensors, and installing new components. In the video chat condition, the on-site participant shared the equipment with the remote expert via live video stream using a handheld device (HHD) and verbally communicated using the video chat. In the AR condition, on-site participants used the HHD to connect with the remote expert, and both participants could communicate verbally or through AR annotations such as drawings, shapes, and notes. On-site users could use annotations to ask questions or show intent, and remote users could use annotations to transmit instructions. The AR-based system resulted in quicker task completion time and lower mental effort.

Despite these promising findings, there is some evidence suggesting that the technology may differentially impact local technicians and remote experts. For example, Bai et al. (2020) investigated different communication cues in remote collaboration environments. Remote experts could communicate instructions to the local worker using eye gaze, where a line representing the remote expert's gaze direction would be overlaid on the local worker's AR view, and/or hand gestures, where the remote expert's hand movements would be displayed through the local worker's AR view. The authors found that task completion time and workload ratings were better using AR cues than only verbal instruction; however, remote users reported higher levels of workload than local users in the AR condition.

Similarly, Niedermayr et al. (2022) investigated a novel remote collaboration system where the local user wearing a Microsoft HoloLens 2 collaborated with the remote expert wearing an HTC Vive Pro in a shared virtual environment in real time. Remote experts instructed the local user through 14 tasks. Local users scored on the lower end of the workload scales. While scores for the remote experts were still relatively low, they were higher on all scales compared to the local users. The remote experts scored particularly high on the *Mental Demand* subscale suggesting that the virtual representation of the environment made the task more taxing.

User Feedback

Understanding the usability of a system, or the ease in which it can be used efficiently and effectively, is an important step in early iterations of a technology as it allows users to supply feedback on their willingness to accept the new technology. Several studies on XR-enabled remote collaboration found favorable ratings of system usability[4] (J. Kim et al., 2020; Langa et al., 2022; Rigamonti et al., 2021) and/or satisfaction with the performance of the system for both AR and VR (e.g., Loizeau et al., 2021; Troung et al., 2021). However, one study compared ratings between different XR types and found that AR may be viewed more favorably than VR for training on a maintenance assembly task (Gavish et al., 2015).

---

[4] Usability was most often measured using the System Usability Scale (SUS; Brooke 1996).

Cho et al. (2022) developed a remote collaboration system for Building Information Modeling (BIM). The field operator, wearing a Microsoft HoloLens, walked around the field site to view building structures with BIM images superimposed in the user field of view. The office manager (remote expert) could view the field operator's perspective from their desktop computer. Both field operators and office managers favorably rated the system's usability because it helped users identify virtual objects and move virtual objects to their desired location and enabled effective communication between users. Huang et al. (2018) studied a gesture-based MR system for distributed collaboration that offered the capability to render a remote workspace to a local user in real-time. Remote experts used VR HMDs and optical head-trackers to immerse the user in the 3D environment and track hand movements. Local users used a 3D camera to share the workspace to the remote expert and used a 2D monitor to view the remote expert's gestures in the shared virtual space. Participants gave favorable ratings for the system's usability in terms of perception of interaction, perceptions of gestures, ease of use, and ease of learning, among others.

Calandra et al. (2021) investigated the usability of two remote collaboration modalities – partially assisted and fully assisted. Fully assisted remote collaboration refers to the typical one-to-one guidance process where the remote expert walks the local technician through the process step-by-step. In contrast, partially assisted collaboration refers to a situation where the remote expert delivers all AR content and information required to address the issue to the local user from the onset, and only interacts with the local user if they reach another sticking point. Calandra et al. (2021) found that users gave higher usability scores to the partially assisted modality because it allowed technicians to work more quickly and efficiently.

Marques, Silva, Alves, et al. (2022) evaluated the effectiveness of a remote collaboration system in participatory installation tasks, such as installing new filters. The participant acting as the on-site technician used an HHD to connect with the remote expert, who was using a laptop computer. The on-site technician captured the local workspace via the HHD, and the remote expert provided procedural guidance through AR annotations, including sorting annotations (temporal ordering/information clustering), 3D gestures, and step-by-step instructions. While participants had positive views of the AR annotation's utility and helpfulness, there were some concerns about the use of HHD, as it would require facing the device toward the equipment while simultaneously trying to repair it.

Collaboration-Based Metrics

Effective communication, coordination, and interaction is essential to successful collaboration, and even more so when collaborators do not have a shared workspace. Despite the emphasis on collaboration, little research has explored collaboration-based outcomes compared to task-based or user feedback outcomes (e.g., Marques, Silva, Dias, et al., 2022b). Marques, Teixeira, et al. (2022) noted that “While creating the means to support collaboration clearly motivated early research, advances in AR have been limited by new technical developments, which means most of the research efforts, so far, have been focused on creating the enabling technology…” (pg. 620). While effectively measuring collaborative processes is difficult, the few studies that have focused on collaborative behaviors highlight critical takeaways for remote collaboration practices, including communication behaviors and feelings of co-presence (e.g., Iwai et al., 2017; Numan & Steed, 2022)

Fussell et al. (2003) evaluated the impact of different remote collaboration set-ups on communication efficiency in an assembly task. The authors compared five collaboration conditions: side-by-side (local and remote users were in the same room), audio only, head camera with eye tracking (*see-what-I-see* perspective), scene camera (independent view), and head camera plus scene camera. Communication efficiency was measured as the number of spoken words, with fewer spoken words reflecting more efficient and higher quality communication. On average, remote experts did two-thirds of the talking during the assembly task. Remote experts spoke significantly less in the side-by-side condition, but no other significant differences were observed between the other conditions. The local worker spoke significantly more in the audio-only condition and significantly less in the side-by-side condition. Local workers also spoke less in the scene condition and scene plus head camera condition than in the head camera only condition.

Dai et al. (2021) conducted a field experiment on how MR influenced safety risk communication during remote collaboration on a construction site. The on-site worker, using an MR HMD (HoloLens), and the remote expert, using a tablet, communicated potential hazards and violations in the workplace environment using AR annotations. The effectiveness of the HoloLens was compared to phone calls, emails, face-to-face meetings, and video teleconferencing. Users perceived the HoloLens as having produced more accurate risk communication (easier conveying and understanding of messages) than all other forms of communication, with 66% of responses favoring MR over face-to-face meeting, 67% favoring MR over emails, 75% favoring MR over video conferencing, and 80% favoring MR over phone calls. Users also perceived the HoloLens as providing a more efficient means of communication. Despite these findings, only 32% of participants were willing to accept AR for risk communication uses given the current state of technology. The authors suggested this was likely due to unfamiliarity with the product and limitations related to the hardware (e.g., limited field of view, connectivity-related pixelation)—factors expected to improve over time.

Marques, Ferreira, et al. (2022) explored the impact of the virtual characteristics of AR content on collaborative activities. The authors identified five dimensions that could impact the effectiveness of visual AR content: visual complexity, visual impact, clarity, directed focus, and inference support[5]. The authors tested the visual quality of AR content (e.g., drawings, markers) in a scenario in which local users had to remove and install a new fan of a boiler while being guided by a remote expert. Users found that AR content contributed to better situation awareness and understanding of the task. Specifically, the AR content was clear (high visual clarity) and useful (high visual impact) without overburdening users with information (low visual complexity).

Ludwig et al. (2021) studied a prototype application for remote collaboration, shARe-it, which used the HoloLens device. The program allows on-site users to record and share a problem with a remote expert who assists in troubleshooting. After reviewing video of the problem, the remote expert could view the *see-what-I-see* perspective of the on-site worker and communicate via audio, markers, and drawing. Three different conditions were compared during an assembly task: audio only, HoloLens with shared view enabled, and HoloLens with shared view, markers, and drawings enabled. The authors found that verbal instructions did not differ between audio and shared view conditions, though the shared view better supported procedural statements, identification of reference points, and monitoring of task status. While the AR markers were helpful for focusing attention in specific areas, verbal instructions were found to guide more precise actions. Overall, the authors found that the shared view feature had the largest impact on conversational grounding, and that the AR annotations (e.g., markings, drawing) contributed little to communication effectiveness.

Human Factors Considerations

Remote collaboration is a human centric activity that has the potential to present unique human factors challenges because of the blending of virtual and real-world objects—which may impact cognitive and perceptual processes—and the technical hardware (e.g., headset, HHD) that will be used by the worker. For XR systems to be effective and enable new maintenance strategies such as remote collaboration, it is essential that these systems are designed to address known and potential human factors issues. To understand human factors in remote collaboration practices, we reviewed and categorized the human factors issues discussed within the selected articles. Human factors topics were categorized into the following categories and were ordered by prevalence: usability, physical, psychological, safety, and environmental.

Usability. As discussed in the section above on performance metrics, usability measures were frequently employed to assess the effectiveness, efficiency, learnability, and satisfaction of AR, MR, and VR devices for remote collaboration. Usability perceptions were generally favorable (e.g., Cho et al., 2022; Huang et al., 2018); however, one’s level of familiarity with technology may be a determinant of usability and user acceptance (Radmard et al., 2015). Dai et al. (2021) noted that judgements about the acceptability of a new technology are often made quickly, and that the novelty of XR devices may require more time for proper familiarization. Dai et al. reported that 51% of maintenance workers had neutral responses and 17% of maintenance workers had negative responses about the acceptability of an MR HMD (i.e., HoloLens). Conversely, Vorraber et al. (2020) and Key et al. (2022) reported that their samples of

---

[5] Visual complexity is defined as the amount of detail present within the image. Visual impact is defined as the degree to which the image facilitates attention and recall. Clarity is defined as the degree to which the image is easily understandable. Directed focus is defined as the extent to which the image directs attention to an item. Inference Support is defined as the extent to which the image supports generation of new insights.

maintenance workers indicated that they were familiar with using new technologies, which may bode well for adopting XR technologies.

In addition to the technical side of usability, interactions between collaborators can influence the usability and acceptability of remote collaboration strategies. Marques, Silva, Dias, et al. (2021) found that teammate familiarity impacted perceptions of the remote collaboration process. Specifically, teams composed of individuals that knew each other gave higher ratings on ability to express ideas, information understanding, spatial presence, communication, and enjoyment, as well as lower ratings on mental effort compared to teams composed of individuals that did not know each other prior to the collaborative activity. This suggests, as pointed out by del Amo et al. (2020), that being familiar with collaborators and understanding their work style or level of experience can impact the effectiveness and efficiency of remote collaboration.

Physical. Physical side effects can result from exposure to visual inputs in augmented and virtual environments that do not align with one's sensory system, as well as from physical hardware itself (such as headsets). VR sickness, also referred to as cybersickness or simulator sickness, occurs when there is sensory conflict between visual inputs and other vestibular inputs (Chang et al., 2020). The visual information presented by AR, MR, and VR displays have the potential to induce feelings similar to that of motion sickness (Piumsomboon et al., 2018).

G. Lee et al. (2020) examined different view-sharing techniques (i.e., 2D video, 360-degree video, 3D models) for remote collaboration environments involving multiple local users wearing AR headsets and a remote expert wearing a VR HMD. In the 2D video condition, the video stream from the local user's headset camera was shared with the remote expert. In the 360-degree video condition, a 360 camera was mounted on the local user's AR headset to deliver a visual stream of the workspace that was not bound to the local user's view. In the 3D model condition, the workspace was reconstructed in 3D which allowed the remote expert to walk around the virtual space using their HMD. There was no difference between conditions in reported VR sickness for the remote expert. Notably, the 3D model condition displayed better outcomes in terms of completion time, task switching, and usability.

Lin et al. (2020) used stabilization techniques to help improve the visual workspace presented to a remote expert's computer from the local user's AR headset. The authors indicated that workspace visualization for the remote expert should be stable to allow the remote expert to examine the workspace. The remote expert view should be similar to that of the local user to enhance perspective taking, should be in real time, and should be of high visual quality. Sickness ratings did not differ between the stable and non-stable video conditions. However, the scenario involved only brief exposure to the VR environment and a simple workplace setting. Even so, participants in the stable video condition showed higher performance and lower ratings of cognitive workload.

Physical effects stemming from the ergonomics of wearable devices, such as headsets or HMDs, are another reported concern, particularly in situations that call for extended, long-duration use. Key et al. (2022) investigated use of an MR HMD (i.e., HoloLens) for displaying augmented maintenance instructions. While there were positive perceptions for using AR, some aircraft maintenance workers reported concerns over the weight and comfort of the AR HMD. Similarly, Vorraber et al. (2020) found that maintenance workers wearing an AR HMD had to position their heads in an uncomfortable and/or awkward position to give remote experts a proper view of the area of interest. Dai et al. (2021) found that some on-site workers found it hard to wear the AR HMD and walk at the same time.

Psychological. The ability of XR to immerse users in an augmented or virtual world and mimic feelings of “being there” is argued to be a beneficial characteristic of AR, MR, and VR systems. Effectively designed systems may support user processing and performance; however, poorly designed systems may cognitively and perceptually overload users.

Positive psychological effects include reduced cognitive load, better situation awareness, better attention allocation, positive emotional reactions, etc. For example:

> Aschenbrenner et al. (2018) found that using an AR-tablet computer, which allowed remote experts to take screenshots and annotate images, resulted in lower cognitive load for the local worker than an audio-only condition, as it provided a shared visual reference for communication.
>
> Hou et al. (2013) found that the learning curve on an assembly task was shortened when using an AR-based system compared to traditional paper instructions. This suggests that properly designed XR systems can help with cognitive processing of task requirements.
>
> Del Amo et al. (2020) found that their AR collaboration framework—which employed a structured-messaging framework—improved the situation awareness of local technicians. Additionally, Marques, Ferreira, Silva, et al. (2022) found that participants believed that AR-based instructions improved attention and recall of task information.

XR devices in remote collaboration may improve feelings of camaraderie among collaborators. For example, Z. Wang et al. (2021) investigated how local users and remote experts sharing the same perspective (i.e., *see-what-I-see*) impacted teamwork, empathy, and mood. Compared to a 2D mode, where the remote expert monitored task progress via videoconferencing, the collaborative AR system enabled better information understanding and communication, higher levels of empathy, increased positive mood, reduced negative mood, and better performance.

Conversely, cognition, emotion, and perception may be negatively impacted during XR-enabled collaborative activities. For example, Calandra et al. (2021), in their comparison of partially and fully assisted collaboration, found that local workers reported increased frustration and pressure to perform in the fully assisted mode. Specifically, workers reported that having to make the remote expert wait while they were performing a procedure added a sense of frustration and pressure to their task. Additionally, Le Chénéchal et al. (2016) compared a see-through HMD versus a fixed camera for streaming video to a remote expert. While the HMD provided easier mapping of annotations to the equipment and higher sense of presence for users, it resulted in less visual comfort. Similarly, in Cho et al.’s (2022) study, remote experts reported that the narrow field of view of the *see-what-I-see* perspective from the local user impacted their situational awareness and overall understanding of situation.

Safety. Safety-related human factors concerns were identified as issues that may increase on-the-job risk and compromise the safety of the worker. Safety-related concerns included issues such as limited field of view, compromised body positions, and trip/fall hazards. Sara et al. (2022) identified that the limited field of view of an AR HMD may impact the image quality and interpretability of AR content and suggested that larger display size would improve visualization. In concurrence, both De Pace et al. (2019) and Dai et al. (2021) reported concerns over AR HMD’s narrow field of view and suggested the limited visual field may impact visualization capabilities and present issues when working on-site. Additionally, Vorraber et al. (2020) uncovered instances of maintenance workers positioning their heads close to the equipment, which could result in injury depending on the piece of equipment being inspected. Similarly, maintenance workers in the Key et al. (2022) study reported that AR HMD may prevent workers from seeing trip and fall hazards in the workplace.

Environmental. Characteristics of the task setting, such as indoor or outdoor environments, low lighting conditions, and inclement weather, may introduce challenges during the remote collaboration process and limit the task or use case to which different XR devices are applied. Vorraber et al. (2020) noted that the use of an AR HMD in low lighting conditions was a concern, because the tinted glass in the HMD impaired the vision and view of maintenance workers. D'Anniballe et al. (2020) noted that the MR HMD (i.e., HoloLens) did not work well when scanning surfaces in direct sunlight or surfaces that were clear, such as glass. Both Vorraber et al. (2020) and Dai et al. (2021) identified communication between local technicians and remote experts to be a challenge in loud operational environments, often requiring the use of dedicated headphones for adequate audio quality.

Discussion

XR technologies such as AR, MR, and VR have the potential to transform NAS maintenance practices by virtually co-locating physically distanced teammates and ensuring that the right information is accessible. XR can enable remote collaboration and virtual maintenance support strategies, such as remote assistance, virtual inspection, and On-the-Job Training (OJT) that can reduce operational barriers to timely work. The current effort provided a comprehensive look at the current state of the science for XR-enabled remote collaboration. Based on our literature review strategy, we screened 74 articles to understand and document the current state of remote collaboration practices in maintenance, including the maintenance tasks to which the technologies are applied, device displays used by local technicians and remote experts, common interaction and communication modes between users, metrics used to assess remote collaboration performance, and known and potential human factors issues. From these articles, it is clear that the proper use of AR, MR, and VR technologies can help enable effective communication and coordination between local and remote users, as well as recreate realistic collaboration behaviors in real time.

Our review uncovered several trends in the literature. First, XR technologies were used to enable several maintenance support strategies, including remote expert assistance on assembly, replacement, and installation tasks; virtual building and facility inspections; and maintenance training. Second, in terms of device displays, local technicians most often used headsets (e.g., wearable computer glasses, HMDs) and HHDs (e.g., mobile application, tablet computer), whereas remote experts most frequently used desktop computers. Commonly reported AR/MR devices included the Microsoft HoloLens and Magic Leap HMDs, and commonly reported VR devices included the HTC Vive and Oculus[6] Rift. While there were commonalities across studies in terms of device type, the usefulness of a given device may depend on the task (Johnson et al., 2015).

Third, XR technologies enabled communications between local and remote users that were similar to face-to-face experiences also extended beyond traditional communication cues. Audio and video still lead the ways in terms of communication mediums, but research has started to

---

[6] Oculus was acquired by Facebook (now Meta) in 2014. (https://about.fb.com/news/2014/03/facebook-to-acquire-oculus/)

explore more advanced cues such as non-verbal gestures, augmented annotations, and haptic feedback. A shared visual view, particularly the *see-what-I-see* perspective, between local and remote users seems to be a key contributor to mutual understanding and effective information sharing, but additional cues, such as AR markers and drawings, might support verbal instructions and increase the precision of remote expert guidance.

Fourth, empirical evidence suggests that XR technologies offer performance benefits in the remote collaboration process. Compared to traditional remote collaboration methods (e.g., audio/video only), XR methods, in general, displayed equivalent or better task completion time, error, and workload ratings. That is, these methods tended not to negatively impact—and in most cases reduced—the time it took a technician to complete the required task, the number of errors committed during the task, and perceived workload. However, there were some important performance differences between local and remote users. Namely, in studies by Bai et al. (2020) and Niedermayr et al. (2022), remote experts reported higher levels of workload than local users when using AR devices for collaboration, suggesting using AR annotations to communicate may increase the demand placed on remote experts, even though it has positive benefits for performance.

XR devices tended to receive positive user feedback from both local and remote users. Specifically, several studies reported that users had positive perceptions of the technology's utility, helpfulness, ease of use, and ease of learning in facilitating remote collaborations (e.g., Calandra et al. 2021; Cho et al., 2022). Notably, there were some concerns over the usability of HHDs because they do not enable hands-free operations (Marques, Silva, Alves, et al., 2022). That is, HHDs require technicians to hold the device in their hands to display the equipment to the remote expert and set it down when they need to perform a procedure. Additionally, one study suggested that different collaborative paradigms – fully assisted and partially assisted – have different usability ratings. Future research is needed to examine how different remote collaboration processes impact both local technicians and remote experts. Interestingly, collaboration-based outcomes received the least amount of attention in the selected articles. While results did suggest that XR can benefit collaborative behaviors, more work is needed to understand how XR can support effective and efficient communication, knowledge sharing, and mutual understanding between local technicians and remote experts.

Lastly, several critical human factors issues were identified that require attention and future research. We categorized human factors issues into five general categories: 1) usability, 2) physical, 3) psychological, 4) safety, and 5) environmental. Unsurprisingly, usability measures such as the SUS were the most common way in which human factors were assessed. Understanding user perceptions of a technology's ease of use, efficiency, and learnability is an essential first step in establishing the feasibility of a technological solution. While usability ratings of different XR devices were mostly positive, some noteworthy factors impacting usability were familiarity with new technology and teammate familiarity. This points to the importance of not only considering technological factors, but also the human element in the remote collaboration process when using advanced technologies.

Visual and sensory conflicts potentially produced by AR, MR, and VR devices may induce motion sickness, which is a real concern when using XR technologies. That said, VR sickness did not appear to be a common occurrence in the reviewed articles. However, the workplace settings and tasks used in many of the studies may not accurately represent the task environment of most Technical Operations personnel, which can include completing complex procedures in confined areas or wearing a device for an extended period of time. For example, in another review of remote collaboration studies, P. Wang, Bai, Billinghurst, Zhang, Zhang, et al. (2021) noted that approximately 25% of tasks within their identified studies involved actual mechanical parts. Ergonomics was also a human factors concern. For instance, the use of a headset required some technicians to place their heads in awkward positions to properly present the workspace to the remote expert (Vorraber et al., 2020). This not only could cause physical strain but could present a safety issue as well. Additionally, carrying out normal activities, such as walking around a worksite, was reported as more difficult while wearing a headset (Dai et al., 2021). Future research on the physical effects of XR use will require investigation, particularly for instances of extended use and use in less than ideal, operational environments.

Both individual and team-level psychological considerations were identified in our review. At the individual level, XR devices (e.g., headset, tablet) and content (e.g, AR annotations) were found to influence cognitive and attentional processing of users. There was some evidence to suggest that the use of AR-based tools can reduce cognitive workload, direct attention, and improve situation awareness and understanding (e.g., Aschenbrenner et al., 2018; Del Amo et al. 2020; Marques, Ferreira, et al., 2022), all of which are critical contributors to ensuring the procedural guidance offered by remote experts is properly implemented by local technicians. On the other hand, there was also evidence suggesting that certain remote collaboration processes could increase feelings of pressure and frustration in local technicians (Calandra et al., 2021) and that a narrow field of view could negatively impact situational understanding and awareness of the remote expert (Cho et al., 2022). At the team-level, Wang et al. (2021) found that sharing the same visual perspective (i.e., *see-what-I-see)* in an AR-based remote collaboration resulted in higher ratings of teamwork and positive emotion. Given the importance of interpersonal interactions to maintenance support strategies, the benefits of XR may also be realized in team-level outcomes.

Safety and environmental considerations were referenced less often across the articles, but the reported issues represent potential barriers to successful implementation. In multiple studies, local workers reported that the use of HMDs on a work site may present safety concerns for users by narrowing their field of view and/or requiring them to situate their body in compromising positions, increasing fall hazards or injury (e.g., Vorraber et al., 2020). Technical Operations personnel are often required to work in environments characterized by physical hazards (e.g., confined areas, elevated surfaces) and ergonomic hazards (e.g., awkward posture, heavy lift); therefore, ensuring that the addition of HMDs and other devices does not add to the hazard potential is critical. Furthermore, environmental factors such as low visibility/lighting and noise also impacted the efficacy of XR systems and the overall quality of remote collaboration communications. For example, the tinted glasses of HMDs impaired the vision of local workers in low lighting conditions (e.g., Vorraber et al., 2020). Examining how environmental characteristics (e.g., weather, visibility, noise) of NAS facilities and equipment impact the utility of XR devices and virtual maintenance support strategies will be a critical direction of future research.

Future Research

The articles summarized previously in this report demonstrate that significant scientific progress has been made on the use of XR technologies for remote collaboration. Yet, a number of open questions remain to be addressed before widespread use of these technologies in the NAS can be recommended. Human factors issues identified in a number of studies remain an area in need of future investigation. In particular, research is needed to understand the short-term and long-term impacts of XR devices, such as wearable computer glasses or HMDs, on the physical (e.g., sickness, headache, eye strain) and psychological (e.g., loss of situational awareness, attentional tunneling) factors of users. In addition, understanding the use of XR devices in operational settings characterized by different environmental conditions (e.g., daytime vs nighttime, indoor vs outdoor) is critical given the variety and diversity of NAS facilities, systems, and equipment. Furthermore, additional research is needed to understand the knowledge sharing process between collaborators, including how XR can enable effective verbal and non-verbal interactions that enhance mutual understanding, situation awareness, and task performance of local and remote users.

Studies comparing different devices and levels of visualization are also needed. Several studies compared XR to traditional remote collaboration methods (e.g., Aschenbrenner et al., 2018; Asl & Dossick, 2022; Braly et al., 2019; Dai et al., 2021; El Ammari & Hammad, 2019; Hou et al., 2013; Liu et al., 2022), but there is little evidence to guide decisions on the type of device to implement in practice. As such, there is a need for studies comparing different device displays (e.g., headset vs. HHD) and different commercial devices (e.g., HoloLens vs. Magic Leap) to understand the appropriate level of technology and visualization needed for different maintenance support strategies. Commercial AR/MR HMDs may purport to offer similar XR experiences, but typically differ in device specifications, gesture tracking, input methods, field of view, and image quality. Understanding the appropriate level of technology for operational maintenance environments is crucial given the cost and investment that comes with deploying new technologies across a large workforce.

Lastly, in agreement with the sentiment of Marques, Teixeira, et al. (2022), many of the articles in this review focused on the technical side of the remote collaboration process. However, collaborative endeavors are inherently social, so greater attention is needed on the human factor, to understand how XR not only connects physically distanced collaborators but supports joint activities on critical tasks. While collaboration is a somewhat fuzzy concept, it is a human-centered activity that requires effective coordination, communication, and teamwork in support of shared task goals. Current research offers guidance on how XR can support collaborative behaviors (e.g., shared visual view). However, more research is needed to understand how advanced visualizations and cues can enhance the collaboration process.

Conclusion

XR devices have the potential to unlock virtual maintenance and remote collaboration support strategies, such as remote assistance, virtual inspections, and OJT. These innovative technologies can support the Technical Operations workforce and NAS services and systems by ensuring the right information is available at the right time, optimizing the management of limited resources (e.g., the time and availability of experts), and improving the quality of maintenance services. More research is needed before XR devices can be successfully implemented in the NAS. With further investigation, this technology might represent a promising tool for Technical Operations and help increase the efficiency and safety of the NAS.

References

References marked with an asterisk (*) are about extended reality applications specifically in the context of aviation.

References marked with two asterisks (**) were not part of the 74 articles identified in the literature search.

**Anton, D., Kurillo, G., & Bajcsy, R. (2018). User experience and interaction performance in 2D/3D telecollaboration. *Future Generation Computer Systems*, *82*, 77-88.

**Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*, *116*, 103254.

Aschenbrenner, D., Rojkov, M., Leutert, F., Verlinden, J., Lukosch, S., Latoschik, M. E., & Schilling, K. (2018, October). Comparing different augmented reality support applications for cooperative repair of an industrial robot. In *2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (pp. 69-74). IEEE. https://doi.org/10.1109/ISMAR-Adjunct.2018.00036

Asl, B. A., & Dossick, C. S. (2022). Immersive VR versus BIM for AEC team collaboration in remote 3D coordination processes. *Buildings*, *12*(10), 1548. https://doi.org/10.3390/buildings12101548

Bai, H., Sasikumar, P., Yang, J., & Billinghurst, M. (2020, April). A user study on mixed reality remote collaboration with eye gaze and hand gesture sharing. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1-13). https://doi.org/10.1145/3313831.3376550

Bailey, S. K., Johnson, C. I., Schroeder, B. L., & Marraffino, M. D. (2017). Using virtual reality for training maintenance procedures. In *Proceedings of the Interservice/Industry Training, Simulation, and Education Conference* (Vol. 17108, pp. 1-11).

*Bowling, S. R., Khasawneh, M. T., Kaewkuekool, S., Jiang, X., & Gramopadhye, A. K. (2008). Evaluating the effects of virtual training in an aircraft maintenance task. International *Journal of Aviation Psychology*, *18*(1), 104-116. https://doi.org/10.1080/10508410701749506

Braly, A. M., Nuernberger, B., & Kim, S. Y. (2019). Augmented reality improves procedural work on an international space station science instrument. *Human Factors*, *61*(6), 866-878. https://doi.org/10.1177/001872081882446

**Brooke, J. (1996). SUS: A quick and dirty usability scale. In P.W. Jordan, B. Thomas, B. A. Weerdmeester & I. L. McClelland (Eds.), *Usability Evaluation in Industry* (pp. 189-194). London: Taylor & Francis.

**Brown, L. J. (2019). Professional reflection–mixed reality to augment the next generation of aviation professionals. In *Engaging the Next Generation of Aviation Professionals* (pp. 163-180). Routledge.

Calandra, D., Cannavò, A., & Lamberti, F. (2021, May). Evaluating an augmented reality-based partially assisted approach to remote assistance in heterogeneous robotic applications.

In *2021 IEEE 7th International Conference on Virtual Reality (ICVR)* (pp. 380-387). IEEE. https://doi.org/10.1109/ICVR51878.2021.9483849

**Catbas, F. N., Luleci, F., Zakaria, M., Bagci, U., LaViola Jr, J. J., Cruz-Neira, C., & Reiners, D. (2022). Extended reality (XR) for condition assessment of civil engineering structures: A literature review. *Sensors*, *22*(23), 9560.

**Chang, E., Kim, H. T., & Yoo, B. (2020). Virtual reality sickness: a review of causes and measurements. *International Journal of Human–Computer Interaction*, *36*(17), 1658-1682. https://doi.org/10.1080/10447318.2020.1778351

Chen, K., Chen, W., Li, C. T., & Cheng, J. C. (2019). A BIM-based location aware AR collaborative framework for facility maintenance management. *Journal of Information Technology in Construction*, *24*, 360-380. https://www.itcon.org/2019/19

Cho, J., Kim, S., Kim, N., & Kang, S. (2022). Development of a Remote Collaboration System for Interactive Communication with Building Information Model in Mixed Reality. *Applied Sciences*, *12*(17), 8738. https://doi.org/10.3390/app12178738

Dai, F., Olorunfemi, A., Peng, W., Cao, D., & Luo, X. (2021). Can mixed reality enhance safety communication on construction sites? An industry perspective. *Safety Science*, *133*, 105009. https://doi.org/10.1016/j.ssci.2020.105009

**D'Anniballe, A., Silva, J., Marzocca, P., & Ceruti, A. (2020). The role of augmented reality in air accident investigation and practitioner training. *Reliability Engineering & System Safety*, *204*, 107149. https://doi-org.ezproxy.lib.ou.edu/10.1016/j.ress.2020.107149

Del Amo, I. F., Erkoyuncu, J., Frayssinet, R., Reynel, C. V., & Roy, R. (2020). Structured authoring for AR-based communication to enhance efficiency in remote diagnosis for complex equipment. *Advanced Engineering Informatics*, *45*, 101096. https://doi.org/10.1016/j.aei.2020.101096

De Pace, F., Manuri, F., Sanna, A., & Zappia, D. (2019). A comparison between two different approaches for a collaborative mixed-virtual environment in industrial maintenance. *Frontiers in Robotics and AI*, *6*, 18. https://doi.org/10.3389/frobt.2019.00018

El Ammari, K., & Hammad, A. (2019). Remote interactive collaboration in facilities management using BIM-based mixed reality. *Automation in Construction*, *107*, 102940. https://doi.org/10.1016/j.autcon.2019.102940

**Ens, B., Lanir, J., Tang, A., Bateman, S., Lee, G., Piumsomboon, T., & Billinghurst, M. (2019). Revisiting collaboration through mixed reality: The evolution of groupware. *International Journal of Human-Computer Studies*, *131*, 81-98.

Fussell, S. R., Setlock, L. D., & Kraut, R. E. (2003, April). Effects of head-mounted and scene-oriented video systems on remote collaboration on physical tasks. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 513-520). https://doi.org/10.1145/642611.642701

**Fussell, S. R., Setlock, L. D., Yang, J., Ou, J., Mauer, E., & Kramer, A. D. (2004). Gestures over video streams to support remote collaboration on physical tasks. *Human-Computer Interaction, 19*(3), 273-309.

*Gangabissoon, T., Bekaroo, G., & Moedeen, W. (2020, September). Application of augmented reality in aviation: Improving engagement of cabin crew during emergency procedures training. In *Proceedings of the 2nd International Conference on Intelligent and Innovative Computing Applications* (pp. 1-8). https://doi.org/10.1145/3415088.3415120

Gavish, N., Gutiérrez, T., Webel, S., Rodríguez, J., Peveri, M., Bockholt, U., & Tecchia, F. (2015). Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. *Interactive Learning Environments*, *23*(6), 778-798. https://doi.org/10.1080/10494820.2013.815221.

Halder, S., Afsari, K., Serdakowski, J., DeVito, S., Ensafi, M., & Thabet, W. (2022). Real-time and remote construction progress monitoring with a quadruped robot using augmented reality. *Buildings*, *12*(11), 2027. https://doi.org/10.3390/buildings12112027

**Harms, C., & Biocca, F. (2004, October). Internal consistency and reliability of the networked minds measure of social presence. In *Seventh annual international workshop: Presence* (Vol. 2004). Universidad Politecnica de Valencia, Spain.

**Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Advances in Psychology* (Vol. 52, pp. 139-183). North-Holland.

Hatzipanayioti, A., Pavlidou, A., Dixken, M., Bülthoff, H. H., Meilinger, T., Bues, M., & Mohler, B. J. (2019, March). Collaborative problem solving in local and remote VR situations. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 964-965). IEEE. https://doi.org/10.1109/VR.2019.8798201

Hoang, T., Greuter, S., & Taylor, S. (2022, March). An evaluation of virtual reality maintenance training for industrial hydraulic machines. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 573-581). IEEE. https://doi.org/10.1109/VR51125.2022.00077

Hou, L., Wang, X., Bernold, L., & Love, P. E. (2013). Using animated augmented reality to cognitively guide assembly. *Journal of Computing in Civil Engineering*, *27*(5), 439-451. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000184

Huang, W., Alem, L., Tecchia, F., & Duh, H. B. L. (2018). Augmented 3D hands: A gesture-based mixed reality system for distributed collaboration. *Journal on Multimodal User Interfaces*, *12*, 77-89. https://doi.org/10.1007/s12193-017-0250-2

Iwai, D., Matsukage, R., Aoyama, S., Kikukawa, T., & Sato, K. (2017). Geometrically consistent projection-based tabletop sharing for remote collaboration. *IEEE Access*, *6*, 6293-6302. https://doi.org/10.1109/ACCESS.2017.2781699

Jebbar, Y., Belqasmi, F., Glitho, R., & Alfandi, O. (2019, December). A fog-based architecture for remote phobia treatment. In *2019 IEEE International Conference on Cloud Computing Technology and Science (CloudCom)* (pp. 271-278). IEEE. https://doi.org/10.1109/CloudCom.2019.00047

**Johnson, S., Gibson, M., & Mutlu, B. (2015, February). Handheld or handsfree? Remote collaboration via lightweight head-mounted displays and handheld devices.

In *Proceedings of the 18th ACM conference on computer supported cooperative work & social computing* (pp. 1825-1836).

**Kaplan, A. D., Cruit, J., Endsley, M., Beers, S. M., Sawyer, B. D., & Hancock, P. A. (2021). The Effects of Virtual Reality, Augmented Reality, and Mixed Reality as Training Enhancement Methods: A Meta-Analysis. *Human Factors, 63*(4), 706-726. https://doi.org/10.1177/0018720820904229

*Key, K., Ma, M., Towne, C., Choi, I., Hu, P. T., Franzman, S. C., Aguilar, D. R., Schroeder, D. J. & Avers, K. (2022). Preliminary Findings: Application of Maintenance Instructions Displayed in Augmented Reality. In *International Conference on Human-Computer Interaction* (pp. 221-232). Springer, Cham.

**Kim, K., Billinghurst, M., Bruder, G., Duh, H. B. L., & Welch, G. F. (2018). Revisiting trends in augmented reality research: A review of the 2nd decade of ISMAR (2008–2017). *IEEE transactions on visualization and computer graphics*, *24*(11), 2947-2962.

Kim, J., Lorenz, M., Knopp, S., & Klimant, P. (2020, November). Industrial augmented reality: concepts and user interface designs for augmented reality maintenance worker support systems. In *2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (pp. 67-69). IEEE. https://doi.org/10.1109/ISMAR-Adjunct51615.2020.00032

Langa, S. F., Montagud, M., Cernigliaro, G., & Rivera, D. R. (2022). Multiparty holomeetings: Toward a new era of low-cost volumetric holographic meetings in virtual reality. *IEEE Access*, *10*, 81856-81876. https://doi.org/10.1109/ACCESS.2022.3196285

Le Chénéchal, M., Duval, T., Gouranton, V., Royan, J., & Arnaldi, B. (2016, March). Vishnu: Virtual immersive support for helping users an interaction paradigm for collaborative remote guiding in mixed reality. In *2016 IEEE Third VR International Workshop on Collaborative Virtual Environments (3DCVE)* (pp. 9-12). IEEE. https://doi.org/10.1109/3DCVE.2016.7563559

Le Chénéchal, M., Duval, T., Gouranton, V., Royan, J., & Arnaldi, B. (2019). Help! I need a remote guide in my mixed reality collaborative environment. F*rontiers in Robotics and AI*, *6*, 106. https://doi.org/10.3389/frobt.2019.00106

Le, H. H., Loomes, M. J., & Loureiro, R. C. (2016, June). User's behaviours in a collaborative task-real vs. virtual environments. In *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)* (pp. 918-923). IEEE. https://doi.org/10.1109/BIOROB.2016.7523745

Lee, G. A., Teo, T., Kim, S., & Billinghurst, M. (2018, October). A user study on MR remote collaboration using live 360 video. In *2018 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 153-164). IEEE. https://doi.org/10.1109/ISMAR.2018.00051

Lee, G., Kang, H., Lee, J., & Han, J. (2020, March). A user study on view-sharing techniques for one-to-many mixed reality collaborations. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 343-352). IEEE. https://doi.org/10.1109/VR46266.2020.00054

Lee, H., Woo, D., & Yu, S. (2022). Virtual reality metaverse system supplementing remote education methods: Based on aircraft maintenance simulation. *Applied Sciences*, *12*(5), 2667. https://doi.org/10.3390/app12052667

Lee, Y., & Yoo, B. (2021). XR collaboration beyond virtual reality: Work in the real world. *Journal of Computational Design and Engineering*, *8*(2), 756-772. https://doi.org/10.1093/jcde/qwab012

Li, Y., Karim, M. M., & Qin, R. (2022). A virtual-reality-based training and assessment system for bridge inspectors with an assistant drone. *IEEE Transactions on Human-Machine Systems*, *52*(4), 591-601. https://doi.org/10.1109/THMS.2022.3155373

Lin, C., Rojas-Munoz, E., Cabrera, M. E., Sanchez-Tamayo, N., Andersen, D., Popescu, V., Noguera, J. A. B., Zarzaur, B., Murphy, B., Anderson, K., Douglas, T., Griffis, C., & Wachs, J. (2020, March). How about the mentor? Effective workspace visualization in ar telementoring. In 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (pp. 212-220). IEEE. https://doi.org/10.1109/VR46266.2020.00040

Liu, X. W., Li, C. Y., Dang, S., Wang, W., Qu, J., Chen, T., & Wang, Q. L. (2022). Research on Training Effectiveness of Professional Maintenance Personnel Based on Virtual Reality and Augmented Reality Technology. *Sustainability*, *14*(21), 14351. https://doi.org/10.3390/su142114351

Loizeau, Q., Danglade, F., Ababsa, F., & Merienne, F. (2021). Methodology for the field evaluation of the impact of augmented reality tools for maintenance workers in the aeronautic industry. *Frontiers in Virtual Reality*, *1*, 603189. https://doi.org/10.3389/frvir.2020.603189

Ludwig, T., Stickel, O., Tolmie, P., & Sellmer, M. (2021). shARe-IT: Ad hoc remote troubleshooting through augmented reality. *Computer Supported Cooperative Work*, *30*, 119-167. https://doi.org/10.1007/s10606-021-09393-5

*Macchiarella, N. D., & Vincenzi, D. A. (2004). Augmented reality in a learning paradigm for flight aerospace maintenance training. In *The 23rd digital avionics systems conference* (IEEE Cat. No. 04CH37576) (Vol. 1, pp. 5-D). IEEE.

Marques, B., Ferreira, C., Silva, S., Santos, A., Dias, P., & Santos, B. S. (2022). Are the instructions clear? Evaluating the visual characteristics of augmented reality content for remote guidance. *Multimodal Technologies and Interaction*, *6*(10), 92. https://doi.org/10.3390/mti6100092

Marques, B., Silva, S., Alves, J., Rocha, A., Dias, P., & Santos, B. S. (2022). Remote collaboration in maintenance contexts using augmented reality: Insights from a participatory process. *International Journal on Interactive Design and Manufacturing*, *16*, 419-438. https://doi.org/10.1007/s12008-021-00798-6

Marques, B., Silva, S., Dias, P., & Santos, B. S. (2021, October). A toolkit to evaluate and characterize the collaborative process in scenarios of remote collaboration supported by AR. In *2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (pp. 326-327). IEEE. https://doi.org/10.1109/ISMAR-Adjunct54149.2021.00074

**Marques, B., Silva, S., Dias, P., & Santos, B. S. (2022a, June). One-to-many remote scenarios: The next step in collaborative extended reality (XR) research. In *Workshop on Analytics, Learning & Collaboration in eXtended Reality (XR-WALC). ACM International Conference on Interactive Media Experiences (IMX 2022)* (pp. 1-6).

Marques, B., Silva, S., Dias, P., & Santos, B. S. (2022b, March). Does Remote Expert Representation really matters: A comparison of video and AR-based Guidance. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 714-715). IEEE. https://doi.org/10.1109/VRW55335.2022.00208

Marques, B., Silva, S., Rocha, A., Dias, P., & Santos, B. S. (2021, March). Remote asynchronous collaboration in maintenance scenarios using augmented reality and annotations. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 567-568). IEEE. https://doi.org/10.1109/VRW52623.2021.00166

Marques, B., Silva, S., Teixeira, A., Dias, P., & Santos, B. S. (2022). A vision for contextualized evaluation of remote collaboration supported by AR. *Computers & Graphics*, *102*, 413-425. https://doi.org/10.1016/j.cag.2021.10.009

**Marques, B., Teixeira, A., Silva, S., Alves, J., Dias, P., & Santos, B. S. (2022). A critical analysis on remote collaboration mediated by Augmented Reality: Making a case for improved characterization and evaluation of the collaborative process. *Computers & Graphics, 102*, 619-633. https://doi.org/10.1016/j.cag.2021.08.006

**Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, *77*(12), 1321-1329.

Mizuno, K., Kamimura, K., Ebihara, T., Wakatsuki, N., & Zempo, K. (2021, October). 2D-3D transformation of pointing objects based on skeletal body surface models for remote collaboration. In *2021 IEEE 10th Global Conference on Consumer Electronics (GCCE) (pp. 259-262)*. IEEE. https://doi.org/10.1109/GCCE53005.2021.9621900

**Newton, D. C. (2022, May). Human Factors Considerations for Head-Worn Displays in Civil Aviation. In *International Conference on Human-Computer Interaction* (pp. 233-250). Cham: Springer International Publishing.

Niedermayr, D., Wolfartsberger, J., Borac, M., Brandl, R., Huber, M., & Josipovic, P. (2022, October). Analyzing the potential of remote collaboration in industrial mixed and virtual reality environments. In *2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (pp. 66-73). IEEE. https://doi.org/10.1109/ISMAR-Adjunct57072.2022.00023

Numan, N., & Steed, A. (2022, November). Exploring user behaviour in asymmetric collaborative mixed reality. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology* (pp. 1-11). https://doi.org/10.1145/3562939.3565630

Obermair, F., Althaler, J., Seiler, U., Zeilinger, P., Lechner, A., Pfaffeneder, L., Richter, M., & Wolfartsberger, J. (2020, April). Maintenance with augmented reality remote support in comparison to paper-based instructions: Experiment and analysis. In *2020 IEEE 7th International Conference on Industrial Engineering and Applications (ICIEA)* (pp. 942-947). IEEE. https://doi.org/10.1109/ICIEA49774.2020.9102078

Oyama, E., Tokoi, K., Suzuki, R., Nakamura, S., Shiroma, N., Watanabe, N., Agah, A., Okada, H., & Omori, T. (2021). Augmented reality and mixed reality behavior navigation system for telexistence remote assistance. *Advanced Robotics*, *35*(20), 1223-1241. https://doi.org/10.1080/01691864.2021.1976670

*Piumsomboon, T., Lee, G. A., Ens, B., Thomas, B. H., & Billinghurst, M. (2018). Superman vs giant: A study on spatial perception for a multi-scale mixed reality flying telepresence interface. IEEE Transactions on Visualization and Computer Graphics, 24(11), 2974-2982. https://doi.org/10.1109/TVCG.2018.2868594.

Radmard, S., Moon, A. J., & Croft, E. A. (2015, August). Interface design and usability analysis for a robotic telepresence platform. *In 2015 24th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)* (pp. 511-516). IEEE. https://doi.org/10.1109/ROMAN.2015.7333643

Rigamonti, L., Secchi, M., Lawrence, J. B., Labianca, L., Wolfarth, B., Peters, H., Bonaventura, K., & Back, D. A. (2021). An augmented reality device for remote supervision of ultrasound examinations in international exercise science projects: Usability study. *Journal of Medical Internet Research*, *23*(10), e28767. https://doi.org/10.2196/28767

Rose, F. D., Attree, E. A., Brooks, B. M., Parslow, D. M., & Penn, P. R. (2000). Training in virtual environments: Transfer to real world tasks and equivalence to real task training. *Ergonomics*, *4*(4), 494-511. https://doi.org/10.1080/001401300184378

Runji, J. M., & Lin, C. Y. (2019, April). Automatic optical inspection aided augmented reality-based PCBA inspection: A development. In *2019 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT)* (pp. 667-671). IEEE. https://doi.org/10.1109/JEEIT.2019.8717385

Santos-Torres, A., Zarraonandia, T., Díaz, P., & Aedo, I. (2022). Comparing visual representations of collaborative map interfaces for immersive virtual environments. *IEEE Access*, *10*, 55136-55150. https://doi.org/10.1109/ACCESS.2022.3176949

Sara, G., Todde, G., & Caria, M. (2022). Assessment of video see-through smart glasses for augmented reality to support technicians during milking machine maintenance. Scientific Reports, 12(1), 15729. https://doi.org/10.1038/s41598-022-20154-2

Sasikumar, P., Gao, L., Bai, H., & Billinghurst, M. (2019, October). Wearable RemoteFusion: A mixed reality remote collaboration system with local eye gaze and remote hand gesture sharing. In *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (pp. 393-394). IEEE. https://doi.org/10.1109/ISMAR-Adjunct.2019.000-3

**Skarbez, R., Smith, M., & Whitton, M. C. (2021). Revisiting Milgram and Kishino's reality-virtuality continuum. *Frontiers in Virtual Reality*, *2*, 647997.

Tait, M., & Billinghurst, M. (2015). The effect of view independence in a collaborative AR system. *Computer Supported Cooperative Work*, *24*, 563-589. https://doi.org/10.1007/s10606-015-9231-8

Tavakkoli, A., Wilson, B., & Bounds, M. (2020, March). An immersive virtual environment for teleoperation of remote robotic agents for everyday applications in prohibitive environments. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces*

Abstracts and Workshops (VRW) (pp. 371-375). IEEE. https://doi.org/10.1109/VRW50115.2020.00080

Tea, S., Panuwatwanich, K., Ruthankoon, R., & Kaewmoracharoen, M. (2022). Multiuser immersive virtual reality application for real-time remote collaboration to enhance design review process in the social distancing era. *Journal of Engineering, Design and Technology*, *20*(1), 281-298. https://doi.org/10.1108/JEDT-12-2020-0500

Torrence, B., & Dressel, J. (2022, May). Critical Review of Extended Reality Applications in Aviation. In *International Conference on Human-Computer Interaction* (pp. 270-288). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-06015-1_19

Truong, P., Hölttä-Otto, K., Becerril, P., Turtiainen, R., & Siltanen, S. (2021). Multi-user virtual reality for remote collaboration in construction projects: A case study with high-rise elevator machine room planning. *Electronics*, *10*(22), 2806. https://doi.org/10.3390/electronics10222806

*Valimont, R. B., Gangadharan, S. N., Vincenzi, D. A., & Majoros, A. E. (2007). The effectiveness of augmented reality as a facilitator of information acquisition in aviation maintenance applications. *Journal of Aviation/Aerospace Education & Research*, *16*(2), 9.

Van Oosterhout, J., Wildenbeest, J. G., Boessenkool, H., Heemskerk, C. J., de Baar, M. R., van der Helm, F. C., & Abbink, D. A. (2015). Haptic shared control in tele-manipulation: Effects of inaccuracies in guidance on task execution. *IEEE Transactions on Haptics*, *8*(2), 164-175. https://doi.org/10.1109/TOH.2015.2406708

Vorraber, W., Gasser, J., Webb, H., Neubacher, D., & Url, P. (2020). Assessing augmented reality in production: Remote-assisted maintenance with HoloLens. *Procedia CIRP*, *88*, 139-144. https://doi.org/10.1016/j.procir.2020.05.025

Wang, P., Bai, X., Billinghurst, M., Zhang, S., Han, D., Lv, H., He, W., Yan, Y., Zhang, X., & Min, H. (2019, October). An MR remote collaborative platform based on 3D CAD models for training in industry. In *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-adjunct)* (pp. 91-92). IEEE. https://doi.org/10.1109/ISMAR-Adjunct.2019.00038

Wang, P., Bai, X., Billinghurst, M., Zhang, S., Han, D., Sun, M., Wang, Z., Lv, H., & Han, S. (2020). Haptic feedback helps me? A VR-SAR remote collaborative system with tangible interaction. *International Journal of Human–Computer Interaction*, *36*(13), 1242-1257. https://doi.org/10.1080/10447318.2020.1732140

Wang, P., Bai, X., Billinghurst, M., Zhang, S., He, W., Han, D., Wang, Y., Min, H., Lan, W., & Han, S. (2020). Using a head pointer or eye gaze: The effect of gaze on spatial AR remote collaboration for physical tasks. *Interacting with Computers*, *32*(2), 153-169. https://doi.org/10.1093/iwcomp/iwaa012

Wang, P., Bai, X., Billinghurst, M., Zhang, S., Wei, S., Xu, G., He, W., Zhang, X., & Zhang, J. (2021). 3DGAM: Using 3D gesture and CAD models for training on mixed reality remote collaboration. *Multimedia Tools and Applications*, *80*(20), 31059-31084. https://doi.org/10.1007/s11042-020-09731-7

**Wang, P., Bai, X., Billinghurst, M., Zhang, S., Zhang, X., Wang, S., He, W., Yan, Y., & Ji, H. (2021). AR/MR remote collaboration on physical tasks: A review. *Robotics and Computer-Integrated Manufacturing*, *72*, 102071.

Wang, P., Wang, Y., Billinghurst, M., Yang, H., Xu, P., & Li, Y. (2023). BeHere: a VR/SAR remote collaboration system based on virtual replicas sharing gesture and avatar in a procedural task. *Virtual Reality*, 1-22. https://doi.org/10.1007/s10055-023-00748-5

Wang, Z., Wang, Y., Zhang, S., & Xiong, Z. (2021). AED: A novel visual representation based on AR and empathy computing in manual assembly. Rev*ista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería*, *37*(1). http://doi.org/10.23967/j.rimni.2021.01.005

Zenati-Henda, N., Bellarbi, A., Benbelkacem, S., & Belhocine, M. (2014, April). Augmented reality system based on hand gestures for remote maintenance. In *2014 International Conference on Multimedia Computing and Systems (ICMCS)* (pp. 5-8). IEEE. https://doi.org/10.1109/ICMCS.2014.6911258

Zhu, Z., Li, J., He, W., Yu, S., & Ma, Y. (2022, July). Research on remote guidance of hardware operation and maintenance of computer room based on AR. In *2022 Global Conference on Robotics, Artificial Intelligence and Information Technology (GCRAIT)* (pp. 373-376). IEEE. https://doi.org/10.1109/GCRAIT55928.2022.00085