SOAR

STATE-OF-THE-ART REPORT (SOAR)
APRIL 2024

CSIAC-BCO-2024-507

EXTENDED REALITY FOR MAINTENANCE AND REPAIR TRAINING

By Joseph M. Friar and Olutoye Sekiteri
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JOSEPH M. FRIAR AND OLUTOYE SEKITERI

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14. ABSTRACT
Extended reality (XR) is an all-encompassing term that groups three similar technologies: (1) virtual reality (VR), (2) augmented reality (AR), and (3) mixed reality (MR). While XR is a field that has been in development in the U.S. Department of Defense (DoD) since the late 1960s, it has continued to see major advancements in recent years. This transformative technology has already made an impact across the DoD and holds considerable potential to improve the defense sector in the coming years. This report explores the current landscape of XR technology and discusses its applications in maintenance and repair within the DoD. In addition, current technological advancements made by impact players in the XR space are showcased, accompanied by research from academic journals and scientific reports. By examining both the benefits and the challenges, this report highlights how VR, AR, and MR are already transforming defense space by providing cost savings, time efficiency, and risk reduction to a variety training programs in the defense industry. With the recent developments in the field of XR, the DoD will be presented with opportunities to harness the capabilities of technology to enhance training programs and maintenance procedures.

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ABSTRACT

Extended reality (XR) is an all-encompassing term that groups three similar technologies: (1) virtual reality (VR), (2) augmented reality (AR), and (3) mixed reality (MR). While XR is a field that has been in development in the U.S. Department of Defense (DoD) since the late 1960s, it has continued to see major advancements in recent years. This transformative technology has already made an impact across the DoD and holds considerable potential to improve the defense sector in the coming years. This report explores the current landscape of XR technology and discusses its applications in maintenance and repair within the DoD. In addition, current technological advancements made by impact players in the XR space are showcased, accompanied by research from academic journals and scientific reports. By examining both the benefits and the challenges, this report highlights how VR, AR, and MR are already transforming defense space by providing cost savings, time efficiency, and risk reduction to a variety training programs in the defense industry. With the recent developments in the field of XR, the DoD will be presented with opportunities to harness the capabilities of technology to enhance training programs and maintenance procedures.

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SECTION 01 INTRODUCTION

A prototype for a head-worn display was developed to assist military mechanics when performing maintenance tasks on armored vehicles [1]. The display was able to guide users through complicated procedures by providing visual elements such as text, labels, and other indicators. To determine the effectiveness of the device, a study was conducted while the mechanics worked on their tasks using the headset. It was found that those using the prototype were able to complete tasks more efficiently and that the mechanics felt the technology was "intuitive and satisfying for the tested sequence of tasks." This is one of many examples of how extended reality (XR) can be integrated into existing maintenance procedures to improve overall performance.

XR is an emerging technology with many potential use cases for organizations across the U.S. Department of Defense (DoD). XR has been acknowledged as a transformative force, having the capability to shape the way users perceive and interact with physical and digital elements. As this sector continues to mature, XR software will become increasingly vital in DoD operations, particularly in maintenance and repair training. This report provides an overview of XR, explores its current and future usage in maintenance and repair training, and provides a snapshot of the current impact players in the field of XR for maintenance and repair training with specific application for the DoD.

1.1 DEFINING XR

XR is an all-encompassing term used to describe virtual reality (VR), augmented reality (AR), and mixed reality (MR). XR refers to all combined real and virtual environments and human-machine interactions generated by computer technology and wearables [2].

In 1994, Paul Milgram and Fumio Kishino introduced the concept of the virtuality continuum, similarly presented in Figure 1-1 [3]. The framework places the three primary areas of XR relative to the level of immersion provided by the technology. However, it is important to note that there are distinct differences between VR, AR, and MR, which can be better described using individual definitions.

1.1.1 VR

VR provides the user with a digital, simulated environment by using a headset or goggles that completely obstruct the view of the physical world [2]. This allows for a fully immersive experience in a digital space. VR is a computer-simulated experience in which computer technologies use reality headsets to generate realistic sensations and replicate a real environment or create an imaginary world (Figure 1-2) [4]. An actual VR environment engages all five senses.

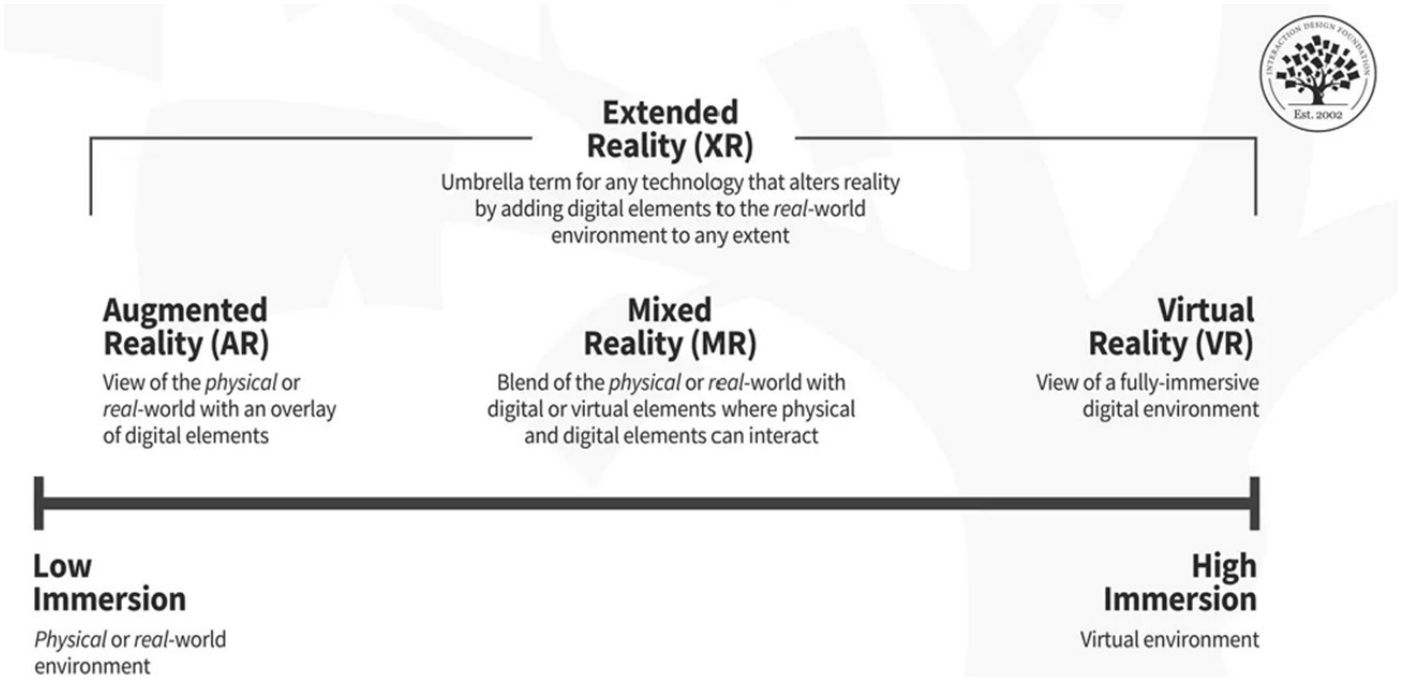

Figure 1-1. Representation of Current XR Technologies According to the Spectrum of Immersion *(Source: Tremosa [3])*.

Figure 1-2. A User Tries a Virtual Reality Simulation for Manufacturing Parts *(Source: Conrad [4])*.

1.1.2 AR

Computer scientist Ron Azuma, known for his contributions in the field of AR, defines the technology as "a field in which three-dimensional (3-D) virtual objects are integrated into a 3-D real environment in real time" [5]. AR provides users with an overlay of digital information onto their view of the physical world [1]. The overlayed information can include images, texts, or 3-D models and is usually viewed through smart glasses, smartphones, or tablets. This allows AR to enhance the real world by adding virtual elements to the field of view without obscuring the physical world (Figure 1-3) [6].

1.1.3 MR

MR provides the user with an experience that combines both VR and AR in a seamless manner [2]. This is accomplished by projecting virtual objects onto the real world and allowing users to interact with them. Mixing both technologies creates a unique environment in which virtual and physical elements can be integrated into the same space. Sometimes called a hybrid reality, MR merges the real and virtual worlds to create new atmospheres and visualizations to interact in real time. One critical characteristic of MR is that artificial and real-world content can respond to one another in real time.

Figure 1-3. A User Wears an AR Headset to Speak to Someone in San Diego for Help With Fixing a Generator *(Source: White [6])*.

1.2 ADVANTAGES OF XR

The Cybersecurity and Information Systems Information Analysis Center has found that XR can enhance maintenance and repair procedures to streamline education, reduce costs, save time, and minimize risks. The technology can provide real-time visual assistance to enhance training efforts by presenting users with mission-critical information. XR also allows for adaptive learning modules, providing personnel with specific user-tailored learning experiences that can enhance student readiness. AR allows remote assistance to be available to technicians in the field, aiding them with visual guidance or communication with experts when performing complex maintenance procedures in real time. XR technologies have allowed new and innovative solutions for maintenance and repair training to emerge within the DoD, bringing a new wave of tools that can benefit many areas of operation.

1.2.1 Streamlining Education

XR technology is now used in classrooms and organizational training to supplement traditional teaching methods. Vectrona, the winner of three Small Business Innovation Research (SBIR) contracts involving innovative training solutions, has stated that AR and MR "training can vastly improve the quality of academic classroom training and task rehearsals" [7]. XR technologies provide these improvements by:

- Reducing the time spent in classroom training
- Allowing students to train, even when physical equipment is not available
- Enabling students to do preliminary training rehearsals prior to live training on physical assets
- Preparing students to get the greatest possible value out of hands-on training opportunities

Another study regarding XR supplementing remote education methods also concluded that trainees using VR were able to retain more information compared to trainees using educational videos [8]. A VR metaverse system was suggested in the study, in which users could immerse themselves and interact with virtual objects. This system was designed to facilitate the safe simulation of complex tasks, which would otherwise require substantial resources to be used in the real world. The system could be integrated into education to enhance learning processes using simulated exercises. Researchers determined the effectiveness of the technology when applied to education by creating an aircraft maintenance simulator. For the study, users with no prior experience were asked to take part in the VR-enabled training session and complete a knowledge acquisition test afterward, as well as a knowledge retention test 10 days later. Another group was asked to attend a video-based training session and had to take the same tests as the other group. The results showed that the group using the VR training scored significantly higher on both tests, indicating that the VR-enabled training method could prove more effective than traditional video training. Based on these studies, users benefit more from hands-on instructed learning with XR compared to traditional learning methods such as PowerPoints or videos.

1.2.2 Reducing Costs

A major factor that plays a huge role in decision-making and the bottom line is cost. The cost of traditional military training tends to be quite expensive and requires attention to planning the training exercise and logistics for all the equipment and personnel involved. According to Mattock et al. [9]:

> [The] training cost for a basic qualified pilot can range from $5.6 million for an F-16 pilot to $10.9 million for an F-22 pilot. Bomber pilot training cost is also high, ranging from $7.3 million for a B-1 pilot to $9.7 million for a B-52 pilot. Transport and mobility pilot training costs are somewhat lower, ranging from $1.1 million for a C-17 pilot to $2.5 million for a C-130J pilot. Training cost per pilot for command, control, intelligence, surveillance, and reconnaissance operations (e.g., the RC-135) is about $5.5 million.

XR technology used for training can significantly reduce the cost associated with planning and operating a training exercise. With the rise of telework and remote collaboration, communicating with XR technologies is becoming more common. The shift in perspective toward XR solutions has made organizations more open to adopting the technology. XR training reduces the cost of travel and commuting for personnel. Whether a sponsoring organization is paying or the cost comes out of pocket, XR eliminates the need for travel in certain training instances and provides a platform for trainees, instructors, and others to collaborate seamlessly.

1.2.3 Minimizing Risk

There is a risk factor associated when training new engineers on repairing military equipment. If equipment is not being maintained and repaired in the correct manner, the engineer could be injured or expensive equipment could be damaged. By leveraging virtual environments in maintenance training, users can familiarize themselves with complex machinery and hazardous environments before working on real equipment.

An inspector general's report [10] advocates for improved training and guidance when it comes to the storage and care of military parts and components. Inspectors found two thirds of $1.96 billion worth of equipment stored at the Defense Logistics Agency (DLA) distribution centers showed critical deficiencies. Overall, $1.8 billion of inspected equipment was unsafe to use due to failure to follow Pentagon standards at DLA storage facilities. XR technology could help address situations like these, as it provides solutions that can improve a technician's productivity, reduce operation errors, enhance the safety of maintenance/repair operations, and ensure overall compliance with industry-specific standards.

XR also facilitates access to information for engineers when performing maintenance tasks in real time, which can prevent safety incidents caused by poor maintenance. In a concept study, researchers found that "12% of serious aircraft accidents and 50% of engine-related flight delays and cancellations were caused by maintenance deficits. Complex routines of aircraft maintenance and repair not only increase costs but also pose a risk to aircraft safety" [11]. To help address this issue, an MR system was created to leverage digital aircraft components and provide users with guidance during inspection processes. Using MR, the digital model of the aircraft component could be overlayed on the physical version, allowing for efficient comparison. The system included a visual interface that provided instructions during maintenance procedures, remaining present on the user's field of view for ease of access. The inspector also had the ability to add marks to damaged sections of a component, which would be stored in the system's database and reflected on the digital version of the part.

While wearing a VR headset or AR glasses or with the help of a tablet or smartphone, technicians can be presented right in their field of view with guiding videos and tips that aim to aid in the maintenance process. Having a step-by-step walkthrough displayed in a real-world view while conducting maintenance tasks greatly increases technician accuracy. Artificial intelligence (AI) software paired with a camera can scan equipment and compare it to a corresponding digital twin stored in the backend. This allows the software to detect issues, imperfections, and damage to the equipment before becoming critical. Knowing the equipment status allows a technician to conduct positive preventative/corrective maintenance and repair. XR technology could become an essential component to minimizing risks associated with equipment management and other training procedures within the DoD.

1.2.4 Saving Time

XR technology also reduces the time to complete various maintenance and training tasks. Android and iPhone operating system (better known as IOS) devices already reduce downtime and improve efficiency, and XR technologies seek to continue that trend. Using real-time visuals such as pictures, videos, and step-by-step instructions helps reduce the amount of time needed for completing tasks and troubleshooting.

Another benefit of XR is the ability to share one's view with others. This allows other professionals to see what someone else is seeing and provides hands-on guidance, eliminating the need to wait for help from on-site personnel. For example, Boeing's aircraft from the 737 to the 787 have hundreds of miles of wiring that run through every new aircraft in different configurations. Placing these wires requires a high level of precision and accuracy, with little margin for error [12]. This task can add up to tens of thousands of work hours per year. To reduce the cognitive load, Boeing has implemented Google Glass and Upskill Skylight to give Boeing's technicians the correct instructions without the need to look away at a laptop or smartphone. "Bar code readers and the Glass cameras help identify and confirm wiring inventory. When extra help is needed, workers turn on Skylight's 'See What I See' video stream and share their view with engineers or other remote experts" [13]. Boeing claims that, by implementing these technologies, it was able to slash production time by 25%.

1.3 CHALLENGES IN XR

Along with the many benefits to using XR technology in training and maintenance, there are still challenges that need to be addressed. One common challenge of this technology is the strain on the body after wearing an XR headset for a prolonged period. Some health risks that may arise include, but are not limited to, headaches, neck pain, eye strain, motion sickness, and fatigue [14]. XR applications should only conveniently fill a user's field of view with necessary information, not overwhelm it. Developers have not yet perfected crafting heads-up displays for the user. Another notable challenge XR faces is the visual detection of equipment and machine part status. For these algorithms to be successful in detecting small details in a real-world view, highly effective image-processing algorithms need to be accurate and reliable with little to no error [15]. Uptime and connectivity can become a problem while collaborating with team members or asking for training or maintenance assistance. The current cost of capable high-fidelity XR headsets is particularly high and can be a few thousand dollars for one unit.

The Naval Research Laboratory was the first organization in the DoD to test XR equipment and determine how it could be used to enhance training programs [16]. The lab tackled many challenges that were presented by XR hardware, such as graphics, depth perception, and portability. One of the main concerns with wearable displays

was the brightness and contrast and being able to provide a clear visual, regardless of outdoor lighting. Engineers had to ensure that the display did not emit too much light into the wearer's eyes to compete with external sunlight. Interactivity with XR systems was a focus, making sure that applications had intuitive controls that users could learn efficiently. For instance, if soldiers looked down at their feet while using an AR system, they would be able to open a map in their field of view for route planning.

SECTION 02 IMPACT PLAYERS

This section provides developments achieved by organizations in the XR field, including recent accomplishments and ongoing efforts.

2.1 IMPACT PLAYERS FOR XR IN MAINTENANCE AND REPAIR

The following subsections give brief summaries of organizations that are impact players in XR for maintenance and repair training, with specific applications to the DoD. These organizations have been found to have projects, research, patents, or technology that support DoD efforts. The organizations are presented alphabetically.

2.1.1 Boeing

Boeing has developed AR technology to facilitate rapid maintenance of deployed aircraft [17]. The company named it the Augmented Training Operations Maintenance (ATOM) technology, and it was tested during the Mobility Guardian 2023 exercise conducted by the U.S. Air Force (USAF) Air Mobility Command. ATOM was used for remote support to assist engineers while they performed maintenance on a USAF C-17. The technology allowed an expert representative to provide holographic instructions over 800 miles away from the aircraft. Through AR-enabled guidance, voice commands, and hand gestures, the user was able to benefit from the technology during the maintenance session. The successful trial highlighted the practical application of AR in addition to the benefits it can have when used for aircraft maintenance. By reducing aircraft downtime, enhancing mission readiness, and fostering collaboration, AR can become an integral tool for the success of field engineers.

2.1.2 Defense Advanced Research Projects Agency (DARPA)

DARPA has invested in solutions that combine AR and AI to create "virtual partners" for military personnel [18]. The program, named Perceptually Enabled Task Guidance (PTG), allows for an AI assistant to provide critical data and instructions to the user's field of view. For maintenance and repair, PTG would allow engineers to follow detailed instructions and visuals to accomplish complex tasks. The agency announced its funding opportunity in 2021 and has allocated a total of $40 million to create this AI-powered AR tool. Other notable technologies implemented in the project included deep learning, video analysis, and automated reasoning. The agency is forecasting a future in which all military personnel will have an AR display that provides essential mission data in real time.

2.1.3 DiSTI

DiSTI provides XR software products for a variety of training scenarios, including virtual maintenance training, virtual operations training, guided field services augmentation, and safety training [19]. The company was awarded a contract in 2020 by the U.S. Army for the Family of Maintenance Trainers Diagnostic Troubleshooting Trainers, which is being used to create virtual training to

teach skills such as fault diagnostics, troubleshooting, and repair. The contract was for indefinite delivery/ indefinite quantity, with an initial ceiling of $42.5 million [20]. The company's XR solutions are helping military customers improve their training by focusing on skill transfer, knowledge retention, and data-driven applications. These solutions are designed to reduce costs and increase operational efficiency. DiSTI has also developed VE Studio, a development platform that end users can utilize to create their virtual training solutions, which could drastically reduce team size if the customer wants to create its own training content.

2.1.4 EON Reality

EON Reality is a software company focused on providing AR and VR solutions to sectors such as the DoD that can benefit from technology [21]. In 2020, the organization was awarded a contract through the USAF AFWERX program, which provided 3-D models and VR content. USAF technicians also adopted EON's XR platform for immersive maintenance training specifically tailored for the F-16 aircraft. The software allowed users to practice repairing complex systems within the F-16 and provided students with interactive information. When using the application, users can select individual 3-D models of the aircraft. When looking at the cockpit, for instance, the engineer can interact with specific controls, buttons, and other crucial elements. The platform supports both VR and AR modes, allowing for different levels of immersion.

2.1.5 Grid Raster Inc.

Grid Raster Inc. is a developer of cloud-based XR platforms, which have earned it multiple SBIR Phase I contract awards valued at around $50,000 each. The contracts involve the development of "a high-performance scalable AR/VR/MR platform for aircraft repair and maintenance, advanced visualization, and simulated training" [22] and "a cloud-based XR operational training and testing infrastructure (OTTI) to deliver a unified and shared synthetic environment for USAF pilot training" [23]. The organization was also awarded an SBIR Phase II contract with the USAF, valued at around $750,000 [24]. The contract aimed to enhance aircraft wiring maintenance for the USAF CV-22 Osprey aircraft using the company's AR toolset. To support the Phase II effort, Grid Raster developed a prototype AR toolset to assist engineers in navigating the intricate wiring systems of the CV-22 [25].

2.1.6 King Crow Studios

King Crow Studios specializes in XR-powered training and software development. The company develops immersive training solutions that utilize XR technology, producing effective learning modules that improve retention and reduce costs [26]. It exclusively uses its own Structured Training and Evolved Process (known as S.T.E.P.) platform to create reliable training experiences. The studio is an "SBIR Phase III award-winning solutions provider for the [DoD]," creating interactive learning modules with a high level of detail. King Crow Studios has also developed XR-enabled training programs for industrial, education, law enforcement, and medical fields, proving that the technology has valuable use cases across many different sectors. King Crow Studios recently announced it had won an SBIR Phase III contract from the USAF to develop immersive training solutions. The studio is the first XR firm in Louisiana to earn the award, which was launched in May 2021 and will run until 2025. The contract, worth $6.5 million, will back the development of B-52 pilot training programs using MR technologies over 4 years. The USAF, along with Nexus Louisiana and Precision Procurement Solutions, supported the bidding process for the contract. The B-52 virtual reality procedures trainer (VRPT) uses an MR platform, simulating the aircraft and its equipment, to train pilots and technicians on procedures before on-site instruction. King Crow Studios' VRPT program aims to cut on-site training costs for the USAF, along with fuel expenses and equipment downtime.

2.1.7 Mass Virtual

Mass Virtual was awarded a 5-year, $59-million contract to develop interactive training modules, virtual models for aircraft, and other vehicles for the USAF Integrated Technology Platform [27]. Mass Virtual is an example of providing XR training content that can have a great return on investment when implemented into the DoD [28]. Its training products currently reach over 24,000 students per year, providing reductions in aircraft training downtime and classroom hours and an increase in student retention. Mass Virtual has also delivered a wide variety of training solutions based on industry needs, including nuclear power plant operations, aircraft preflight procedures, space systems operations rehearsal, undersea vehicle models, and aircraft engine models.

Mass Virtual has collaborated with the Air Force Special Operations Command (AFSOC) to establish new training frameworks that make use of XR technology [29]. The Virtual Hangar is a training platform developed by the company to facilitate initial qualification training for all aircrew and mission support personnel. The platform supports VR training for the AC-130J, MC-130J, and CV-22, allowing munition maintenance crews to train using a variety of tools and learning modules. Mass Virtual has also developed other virtual training experiences, including a C-17 loading bay simulator and an explorable full-scale model of the C-5M aircraft.

2.1.8 Naval Air Systems Command

The Naval Air Warfare Center Aircraft Division is developing AR headset applications that can connect experts with maintainers globally, aiming to enhance the maintenance and repair processes in the Navy [30]. The organization was recognized in 2020 with the DoD Maintenance Innovation Challenge Award for developing the Augmented Reality Remote Maintenance Support Service (ARRMSS). The system facilitates real-time collaboration through audio and visual communication between engineers using AR headsets and allows fleet maintainers to troubleshoot issues with the assistance of holographic overlays. ARRMSS is being tested to operate in low-bandwidth networks, allowing it to remain functional at sea and in other challenging environments. This feature has allowed the technology to stand out from other XR products and has generated interest from other service branches in the DoD.

2.1.9 Raytheon

VirtualWorx is an AR tool developed by Raytheon for defense training and simulation [31]. The focal use case for this effort is remote communication using AR, which connects users with experts to facilitate remote maintenance, remote technical assistance, remote inspection, and supplier support. VirtualWorx has been able to create many solutions for customers by providing them with an effective remote communication tool and has become a favorable platform for end-to-end AR collaboration "to support the maintenance of aerospace and defense repairable assets." The technology streams live video and audio between engineers, subject matter experts, and other parties involved in the operation, using virtual private networking (better known as VPN) to secure information being exchanged remotely. The system has been used for the maintenance of U.S. Navy ships by aiding in diagnosing and repairing complex systems. When working on a decommissioned Navy destroyer, a technician on board was able to receive detailed instructions remotely from an expert via the AR display.

2.1.10 Taqtile

Manifest is a software solution developed by Taqtile, which "improves operational workflows so that jobs get done more accurately and consistently" [32]. Field workers can use the software's special computing capabilities to access maintenance data

on any device. This allows customers to choose the hardware that is best suited for their needs, whether they prefer the hands-free solution that AR glasses provide or the accessibility of a tablet. The software was designed to allow experts to build AR work instructions efficiently, requiring no coding or computer-aided design skills to produce training modules with Manifest. The software also allows for remote assistance using video streaming, which is optimized to function in low-bandwidth settings.

Manifest has been used by DoD organizations to enhance maintenance and training operations by providing engineers with visual guidance via AR. For instance, the tool was used by Booz Allen Hamilton in the U.S. Army Join Base Lewis-McChord 5G AR training program [33]. The DoD invested $600 million into this effort to test the capabilities of 5G and AR technologies when deployed in military settings. Taqtile was a notable part of this project, as its software was used by the program to store detailed maintenance and repair procedures that made use of AR [34]. Manifest was also used to perform maintenance on an M1 Abrams tank, allowing the mechanic to access work instructions in real time using the AR software [35].

The USAF implemented Taqtile's AR solution to train jet engine mechanics [36]. The Air Force Institute of Technology conducted a comprehensive study of the impact the Manifest AR platform had on routine technical orders (T.O.). The T.O. information was converted into AR content on the Manifest platform, allowing visual instructions and steps to be displayed in the technician's field of view. While using the Manifest software, engineers were significantly less likely to make errors, showcasing that AR can improve the efficiency of maintenance procedures.

2.1.11 USAF

The USAF has been looking for ways to incorporate VR technology into its training programs [37]. At Sheppard Air Force Base, the Tech Training Transformations team has been looking to use virtual environments to teach complex aircraft maintenance skills. With the assistance of HTX Labs, the team was able to adapt the crew chief fundamentals course into VR content, allowing trainees to learn critical content in a more interactive manner. Users were able to perform maintenance procedures on virtual aircraft models and had access to different modules and tools that enhanced their learning experience. Nonplayable characters were introduced into the project to aid trainees by providing information, such as an instructor would in real life. To determine the effectiveness of the new training course, a test was given to both trainees learning through traditional methods and trainees using the new VR training methods. While both groups had similar results in terms of test scores, the VR trainees were able to complete the course in half the time. This example shows how XR can be used to provide highly interactive training and enhance learning processes across the DoD.

2.1.12 U.S. Army

The Army has integrated MR hardware with guided maintenance that is powered by machine learning [38, 39]. This solution demonstrated the potential to support soldiers when maintaining advanced medium mobile power sources (AMMPS) that are commonly present throughout the military. This effort was led by the U.S. Army Command, Control, Communications, Computers, Cyber, Intelligence, Surveillance, and Reconnaissance Center, using commercial-off-the-shelf (COTS) VR goggles that are equipped with maintenance guidance and troubleshooting steps. While wearing the headset, the MR program provides visual instruction overlayed on the generator to deliver detailed information. The software allows experts to communicate remotely to provide aid during maintenance procedures and has machine learning integration that can modify training content based on data collected. The project also created a "digital twin" of AMMPS, allowing engineers

to practice repairs at any time without being limited by the number of physical AMMPS systems available. When testing the technology during a demonstration, Staff Sgt. Jennifer Woolums stated, "It's going to be easier for a Soldier to troubleshoot, find the initial problem, get the part ordered, and get the piece of equipment up and running in a timely manner. It'll save hours of time. Being able to maximize a Soldier's time is the most important thing" [39]. The Army believes the project could provide many benefits to its personnel, including cost savings and training availability.

2.2 OTHER NOTABLE PLAYERS FOR XR IN MAINTENANCE AND REPAIR

The following subsections give summaries of other notable organizations in XR for maintenance and repair training. These organizations have been found to have projects, research, patents, or technology that have the potential to support DoD efforts. The organizations are presented alphabetically.

2.2.1 CGS

CGS has developed an AR-powered solution aimed at field service workers called TeamworkAR, which can overlay visual training content onto equipment in the user's field of view [40]. This allows educational material to be displayed according to the equipment being viewed, so technicians can focus on the physical components of the learning experience while using AR to assist in the process. The content displayed for the user can range from instructional videos to detailed step-by-step instructions pointing to physical elements. The solution also has remote support capabilities, connecting field technicians with experts who can send instructions via video or voice chat. TeamworkAR could be implemented into DoD operations to enhance the capabilities of field service technicians and maintenance personnel. Overlaying visual training content onto equipment within the user's field of view would allow technicians to expedite the troubleshooting and repair processes in military settings.

2.2.2 L3Harris

L3Harris's virtual maintenance trainer (VMT) was designed to provide efficient training for maintenance operations on commercial aircraft [41]. Maintenance technicians can explore the aircraft virtually, navigate the interior, and conduct real-time component removals to observe outcomes. The VMT has a focus on classroom training by offering instructor-led scenarios and procedure training and encourages collaboration among technicians. The VMT, equipped with a high-fidelity cockpit simulator and interactive capabilities, significantly contributes to the students' learning of the cockpit and development of spatial awareness. This technology has the potential to support engineers maintaining military aircraft, while also increasing their knowledge and understanding of aircraft maintenance practices. The addition of VMT modules to existing DoD curriculum could allow students to benefit from highly interactive learning experiences.

2.2.3 Oberon Technologies

Oberon Technologies has developed VR training solutions for several technical fields and topics such as fire equipment training, lockout/tagout procedure training, hazardous or dangerous environments training, training for energy gas utilities, and more [42]. The company can quickly implement immersive courses that address common needs such as Occupational Safety and Health Administration and standard operating procedures training. Another benefit highlighted by the company is the cost savings incurred by users due to the elimination of travel and optimization of instructor working time. The DoD could implement VR training experiences, such as the ones created by this organization, to enhance existing training programs and allow trainees to practice dangerous scenarios in a safe environment.

2.2.4 Scope AR

Scope AR provides maintenance information via its AR solution [43]. Its platform is called Worklink and allows expert guidance to be delivered to any mobile device, whether live by a technician or through a sequential tutorial powered by AR. The system simplifies the creation of AR instruction, providing customers with a no-code interface to build their own immersive educational experiences. Scope AR has worked with prominent customers in different industries such as Unilever, Lockheed Martin, Prince Castle, and Makino. Worklink could be used to shape maintenance procedures and training methodologies across various organizations in the DoD. By leveraging the technology, military engineers in the DoD can be provided with real-time expert guidance and tailored instructions that can be adapted to fit any maintenance procedure.

2.2.5 TeamViewer

TeamViewer created software for remote computer access, which can translate into its latest AR solution called TeamViewer Frontline [44]. The product is an all-in-one AR platform that can allow workers to "speed up processes, decrease error rates, improve quality, and save costs." One specific use case that the company highlights is the use of TeamViewer Frontline to enhance maintenance and repair processes with Frontline xInspect, which can digitalize repair instructions and display the information from the technician's field of view. The AR software includes features such as guided diagnostics, guided troubleshooting, and virtual checklists. Another notable program within the TeamViewer Frontline ecosystem is the xAssist solution, which can remotely connect workers at a job site to technical experts who provide instructions while the maintenance work is being done. Keeping both hands free while performing technical work is crucial for the task objective, and this AR product allows workers to focus on their mission without having to reach for physical manuals. Both xInspect and xAssist can be used as tools to enhance maintenance and repair processes across military operations. Existing maintenance procedures in the DoD can be adapted using the toolsets, allowing field technicians to use AR to have access to critical information when performing repair work.

2.2.6 Vertex Solutions

Vertex Solutions has many ongoing projects focused on XR and its effective application in different use cases [45]. The company works across multiple domains and has implemented XR training successfully in different technical fields. Its solutions aim to be hardware agnostic to ensure that the right hardware is used in each training use case. In the context of maintenance and repair training, it is developing the AFSOC AC-130J maintenance trainer. This specific training solution plans to help train technicians with complex tasks regarding aircraft repair. The company hopes that this training will provide valuable practice to the trainee without risk to the individual or the aircraft. Many organizations across the DoD could benefit from implementing XR-enabled maintenance trainers into their training programs, improving personnel readiness and proficiency during maintenance procedures.

2.3 XR HARDWARE

Table 2-1 provides a list of notable hardware in the XR sector. The items have been divided into VR, AR, and MR. The hardware listed is COTS available and either supports or has the potential to support DoD efforts. It is important to note that a display, motion tracker, and image generator may be needed for a complete system and not all product packages include these components.

Table 2-1. Notable COTS XR Hardware *(Source: Brown [46])*

Company	Product	Category	Price	Release Date	Resolution	Refresh Rate
HTC	VIVE XR Elite	VR	$1,099.00	March 2023	3840 × 1920	90 Hz
	VIVE Pro 2	VR	$1,399.00	June 2021	4896 × 2448	120 Hz
Meta	Meta Quest Pro	VR	$999.00	October 2022	3600 × 1920	90 Hz
Valve	Valve Index	VR	$999.00	April 2019	2880 × 1600	144 Hz
Magic Leap	Magic Leap 2	AR	$3,299.99	September 2022	2880 × 1760	—
Lenovo	ThinkReality A3	AR	$1,499.99	November 2021	3840 × 1080	—
Vuzix	BLADE 2	AR	$1,299.99	September 2022	960 × 480	—
Apple	Apple Vision Pro	MR	$3,499.99	February 2024	7320 × 3200	90 Hz
Meta	Meta Quest 3	MR	$649.99	October 2023	4128 × 2208	120 Hz
Microsoft	Holo Lens 2	MR	$3,500.00	November 2019	2880 × 936	60 Hz

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SECTION 03 CONCLUSIONS

The integration of XR technologies into maintenance and repair efforts across the DoD will have significant benefits to those operations. The organizations discussed in this report have delivered solutions that have had profound results when deployed, regardless of whether using VR, AR, or MR technologies. XR-based training programs have significantly enhanced the way personnel consume training content and have proven that interactive learning modules are usually more effective than traditional learning methods. Allowing technicians to practice maintenance procedures in a virtual environment without the risk of physical harm allows them to focus on the material being taught. The possibilities for XR are seemingly endless, providing immersive training, remote maintenance instruction, and easy access to mission-critical data. The technology has the potential to transform legacy processes throughout the DoD and pave the way for an efficient and XR-enabled future.

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REFERENCES

1. Henderson, S., and S. Feine. "Exploring the Benefits of Augmented Reality Documentation for Maintenance and Repair." *IEEE Transactions on Visualization and Computer Graphics*, vol. 17, issue 10, https://ieeexplore.ieee.org/document/5620905, accessed 22 February 2024.
2. Pepperdine University. "Extended Reality (XR)." *Pepperdine Libraries*, https://infoguides.pepperdine.edu/xr, accessed 28 November 2023.
3. Tremosa, L. "Beyond AR vs. VR: What Is the Difference Between AR vs. MR vs. VR vs. XR?" *Interaction Design Foundation*, https://www.interaction-design.org/literature/article/beyond-ar-vs-vr-what-is-the-difference-between-ar-vs-mr-vs-vr-vs-xr, accessed 19 February 2024.
4. Conrad, K. "Rock Island Arsenal-Joint Manufacturing and Technology Center." *DVIDS: Defense Visual Information Distribution Service*, https://www.dvidshub.net/image/4406576/virtual-reality, 11 May 2018.
5. Shoaib, H., and S. W. Jaffry. "A Survey of Augmented Reality." University of Punjab, Pakistan, 8 January 2015.
6. White, D. R. "Augmented Reality Demonstration." *DVIDS: Defense Visual Information Distribution Service*, https://www.dvidshub.net/image/7393471/augmented-reality-demonstration, 25 August 2022.
7. PTC. "The U.S. Air Force Adopts Immersive Mixed Reality Training to Fuel Better Engagement, Learning Retention, and Outcomes." *PTC*, https://www.ptc.com/en/case-studies/vectrona-immersive-augmented-reality-training-with-us-airforce, accessed 19 February 2024.
8. Lee, H., D. Woo, and S. Yu. "Virtual Reality Metaverse System Supplementing Remote Education Methods: Based on Aircraft Maintenance Simulation." *Applied Sciences*, vol. 12, no. 5, pp. 2667, https://www.mdpi.com/2076-3417/12/5/2667, 4 March 2022.
9. Mattock, M. G., B. J. Asch, J. Hosek, and M. Boito. "The Relative Cost-Effectiveness of Retaining Versus Accessing Air Force Pilots." *RAND*, https://www.rand.org/pubs/research_reports/RR2415.html, 7 March 2019.
10. Office of Inspector General, U.S. Department of Defense. "Audit of the Defense Logistics Agency Storage and Care of Repair Parts and Components for Army Ground Combat Systems." Alexandria, VA, https://media.defense.gov/2023/Oct/24/2003326664/-1/-1/1/DODIG-2024-001%20SECURE.PDF, 13 October 2023.
11. Utzig, S., R. Kaps, S. M. Azeem, and A. Gerndt. "Augmented Reality for Remote Collaboration in Aircraft Maintenance Tasks." *IEEE Xplore*, https://ieeexplore.ieee.org/document/8742228, accessed 22 February 2024.
12. Boland, M. "Case Study: Boeing Cuts Production Time With AR." *AR Insider*, https://arinsider.co/2021/08/24/case-study-boeing-cuts-production-time-with-ar/, 24 August 2021.
13. IoT ONE Limited. "Boeing Cuts Production Time by 25% With Skylight on Glass." *IoT ONE*, https://www.iotone.com/case-study/boeing-cuts-production-time-by-25-with-skylight-on-glass/c1017.
14. U.S. Food and Drug Administration. "Augmented Reality and Virtual Reality Medical Devices: Questions to Consider." *FDA*, https://www.fda.gov/medical-devices/digital-health-center-excellence/augmented-reality-and-virtual-reality-medical-devices-questions-consider#:~:text=It%20is%20important%20to%20use,%2C%20motion%20sickness%2C%20and%-20fatigue, 1 September 2023.
15. ScienceSoft USA Corporation. "Augmented Reality (AR) for Maintenance, Repair, and Overhaul." *ScienceSoft*, https://www.scnsoft.com/augmented-reality/maintenance-and-repair, accessed 20 December 2023.
16. Rosenblum, L. J., S. K. Feiner, S. J. Julier, J. E. Swan II, and M. A. Livingston. "The Development of Mobile Augmented Reality." *Expanding the Frontiers of Visual Analytics and Visualization*, ch. 24, pp. 431–448, edited by J. Dill, R. A. Earnshaw, D. J. Kasik, J. A. Vince, and P. C. Wong, UK: Springer, http://link.springer.com/chapter/10.1007/978-1-4471-2804-5_24, May 2012.
17. Boeing. "Boeing Field Tests Virtual Technology to Rapidly Repair USAF C 17." *Boeing*, https://www.boeing.com.au/featured-content/boeing-field-tests-virtual-technology-to-rapidly-repair-usaf-c-17.page, 24 August 2023.
18. Marge. D. "Perceptually-Enabled Task Guidance (PTG)." *DARPA*, https://www.darpa.mil/program/perceptually-enabled-task-guidance, accessed 20 December 2023.
19. The DiSTI Corporation. "Vehicle, Airframe Maintainer, and Operator Trainers." *DiSTI*, https://disti.com/market-solutions/defense/, accessed 28 November 2023.
20. The DiSTI Corporation. "U.S. Army Awards DiSTI $42.5M Agreement." *DiSTI*, https://disti.com/u-s-army-awards-disti-42-5m-agreement/, accessed 20 December 2023.
21. EON Reality. "US Air Force Maintenance Training in AR and VR." *EON Reality*, https://eonreality.com/us-air-force-maintenance-training-in-ar-and-vr/, accessed 20 December 2023.

REFERENCES, *continued*

22. U.S. Department of Defense. "A High Performance Scalable AR/VR/MR Platform for Aircraft Repair & Maintenance, Advanced Visualization and Simulated Training." *SBIR STTR*, https://www.sbir.gov/sbirsearch/detail/1942413, accessed 7 January 2024.
23. U.S. Department of Defense. "A Cloud-Based XR Operational Training and Testing Infrastructure (OTTI) to Deliver a Unified and Shared Synthetic Environment for USAF Pilot Training." *SBIR STTR*, https://www.sbir.gov/sbirsearch/detail/2172439, accessed 7 January 2024.
24. U.S. Department of Defense. "Prototyping a Scalable High-Precision Augmented Reality (AR) Toolset for CV-22 Nacelle Wiring Harness Installation." *SBIR STTR*, https://www.sbir.gov/sbirsearch/detail/2167611, accessed 7 January 2024.
25. Business Wire. "Grid Raster Inc. Awarded the US Air Force SBIR Phase II Contract to Improve CV-22 Osprey Aircraft Wiring and Maintenance sing Augmented Reality." *Business Wire*, https://www.businesswire.com/news/home/20210921005358/en/Grid-Raster-Inc.-Awarded-the-US-Air-Force-SBIR-Phase-II-Contract-to-Improve-CV-22-Osprey-Aircraft-Wiring-and-Maintenance-using-Augmented-Reality, accessed 7 January 2024.
26. Crow King Studios, LLC. "Transformative Training. Proven Results." *King Crow Studios*, https://kingcrowstudios.com/, accessed 28 November 2023.
27. Daigle, L. "Virtual and Augmented-Reality USAF Training Contract Worth $59 Million Awarded to Mass Virtual." *Military Embedded Systems*, https://militaryembedded.com/cyber/virtual-and-augmented-reality-usaf-training-contract-worth-59-million-awarded-to-mass-virtual, accessed 25 December 2023.
28. Mass Virtual. "Building Experiences That Are Beyond Words: Enhancing Human Performance in an Affordable, Efficient, Safe, and Memorable XR Landscape." *Mass Virtual*, https://massvirtual.com/, accessed 28 November 2023.
29. Mass Virtual. "Virtual HangarTM Transforms AFSOC's Training Landscape." *Mass Virtual*, https://massvirtual.com/virtual-hangartm-transforms-afsocs-training-landscape/, accessed 22 February 2024.
30. Naval Air Systems Command. "Navy Engineers Developing Augmented Reality Headsets to Revolutionize Maintenance and Repair Worldwide." *NAVAIR*, https://www.navair.navy.mil/news/Navy-engineers-developing-augmented-reality-headsets-revolutionize-maintenance-and-repair, accessed 25 December 2023.
31. Raytheon. "A Navy Ready to Fight Tonight." *Raytheon, an RTX Business*, https://www.rtx.com/raytheon/news/2023/07/25/a-navy-ready-to-fight-tonight#:~:text=The%20VirtualWorx%20augmented%20reality%20system,Navy's%20secure%20satellite%20communication%20network, accessed 25 December 2023.
32. Taqtile, Inc. "Empower Deskless Workers." *Taqtile*, https://taqtile.com/company/, accessed 28 November 2023.
33. Taqtile, Inc. "US Army JBLM 5G AR/VR Training." *Taqtile*, https://taqtile.com/case-studies/us-army-jblm, accessed 25 December 2023.
34. PR Newswire. "Booz Allen Hamilton and Taqtile Partner on 5G-Powered AR Deployment at Joint Base Lewis-McChord in Washington State." *PR Newswire*, https://www.prnewswire.com/news-releases/booz-allen-hamilton-and-taqtile-partner-on-5g-powered-ar-deployment-at-joint-base-lewis-mcchord-in-washington-state-301268985.html, accessed 25 December 2023.
35. Taqtile, Inc. "Authoring Augmented Reality Work Instructions on a US Army Abrams Tank." *Taqtile*, https://taqtile.com/case-studies/authoring-instructions/, accessed 25 December 2023.
36. Taqtile, Inc. "Military Aircraft Maintenance Training With Augmented Reality." *Taqtile*, https://taqtile.com/case-studies/jet-engine-maintenance/, accessed 25 December 2023.
37. Vive Business. "What Is the Use of VR in Military Applications? 8 Examples Making the Biggest Impacts." *Vive Business*, https://business.vive.com/us/stories/use-of-vr-in-military/, accessed 29 November 2023.
38. Lafontaine, D. "Army Demonstrates Power of Mixed-Reality Technology for Generator Repairs." *U.S. Army*, https://www.army.mil/article/267676/army_demonstrates_power_of_mixed_reality_technology_for_generator_repairs, accessed 28 November 2023.
39. Manuel, R. "US Army Exploring Mixed Reality Use for Generator Maintenance, Training." *The Defense Post*, https://www.thedefensepost.com/2023/06/29/us-mixed-reality-generator-maintenance/#:~:text='Revolutionizing'%20Maintenance%20Processes,users%20to%20appropriate%20troubleshooting%20steps, accessed 25 December 2023.
40. CGS. "Augmented Reality for Field Services." *CGS*, https://www.cgsinc.com/en/augmented-reality-remote-guidance-and-interactive-support?utm_source=google&utm_medium=ppc&utm_campaign

REFERENCES, *continued*

=TWAR%20-%20Search%20-%20AR%20For%20Field%20Services%20|%20WFX%20-%20CTA%20Experiment&utm_term=maintenance%20vr&gad=1&gclid=EAIaIQobChMIp57T0PzcgQMVx9XICh0VxgirEAMYASAAEgLPTvD_BwE, accessed 28 November 2023.

41. L3Harris Technologies, Inc. "Virtual Maintenance Trainer." *L3Harris*, https://www.l3harris.com/all-capabilities/virtual-maintenance-trainer, accessed 7 January 2024.
42. Oberon Technologies, Inc. "Making Virtually Anything a Reality." *Oberon Technologies*, https://www.oberontech.com/, accessed 28 November 2023.
43. Scope AR. "Augmented Reality in Aerospace & Defense." *Scope AR*, https://www.scopear.com/industries/aerospace-defense, accessed 7 January 2024.
44. TeamViewer Frontline. "Empower Your Frontline Team With Industry-Proven AR Solutions." *TeamViewer*, https://www.teamviewer.com/en-us/products/frontline/?utm_source=google&utm_medium=cpc&utm_campaign=us%7Cnb%7Cpr%7C23%7Caug%7CFrontline-AR%7Ct0%7C0&utm_content=Frontline-AR&utm_term=augmented+reality+for+industry&gclid=EAIaIQobChMIqePy1ofdgQMVhYzICh3jyQmVEAAYAyAAEgKedPD_BwE, accessed 28 November 2023.
45. Vertex Solutions. "Vertex Solutions Awarded Two Contracts From US Navy for Extended Reality Flight Simulators." https://www.vertexsolutions.com/blog/article/2023/09/vertex-solutions-awarded-two-contracts-from-us-navy-for-extended-reality-flight-simulators, accessed 28 November 2023.
46. Brown, R. "VRcompare—The Internet's Largest VR & AR Headset Database." *VRcompare*, https://vr-compare.com/, accessed 28 April 2024.

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BIBLIOGRAPHY

Larson, K. "Using Augmented Reality in the Corporate Environment: A Proposed Study Protocol." 2019 Eighth International Conference on Educational Innovation Through Technology (EITT), pp. 245–249, Biloxi, MS, https://ieeexplore.ieee.org/abstract/document/8924094, 2019.

National Research Council. *Virtual Reality: Scientific and Technological Challenges*. doi:10.17226/4761, edited by N. I. Durlach and A. S. Mavor, Washington, DC: The National Academies Press, https://nap.nationalacademies.org/catalog/4761/virtual-reality-scientific-and-technological-challenges, 1995.

Peng, Y., G. Yu, W. Ni, Z. Lv, Y. Jiang, and J. Chen. "Design and Development of Intelligent Operation and Maintenance Training System for Substation Based on Augmented Reality." *2017 Chinese Automation Congress (CAC)*, pp. 4765–4769, Jinan, China, https://ieeexplore.ieee.org/document/8243621, 2017.

Sabarinathan, K., N. Kanagasabapathy, V. D. Ambeth Kumar, P. K. Rishikesh, R. V. Priyadharshan, and A. Abirami. "Machine Maintenance Using Augmented Reality." 2018 3rd International Conference on Communication and Electronics Systems (ICCES), pp. 613–618, Coimbatore, India, https://ieeexplore.ieee.org/document/8723900?source=IQplus, 2018.

Zhao, P., H. Wu, X. Shi, J. Li, X. Yi, and S. Liu. "Research on Maintenance Guiding System Based on Augmented Reality." 2019 International Conference on Sensing, Diagnostics, Prognostics, and Control (SDPC), pp. 944–949, Beijing, China, https://ieeexplore.ieee.org/document/9168912, 2019.

EXTENDED REALITY FOR MAINTENANCE AND REPAIR TRAINING

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