Augmented Maintenance: Setting Expectations for Augmented Reality

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ABSTRACT

Augmented Reality to support maintenance has been an area of study for over 50 years. In recent years, advances in commercially available hardware platforms offer increased potential value from augmented reality solutions. Like an aircraft heads-up display, Augmented Reality systems insert information in the maintainer's visual field and using a camera, can interpret and provide analysis about events in the user's field of view, potentially sharing that information with a remote collaborator to provide the user with verification, oversight, and assistance. The enhancements provided by Augmented Reality to a maintainer's workflow can range from intuitive access to digital documentation that can increase time on task to real-time computer-assisted visual assessments that reduce both maintainer cognitive load and likelihood of errors. However, Augmented Reality platforms can vary drastically in terms of capabilities and the effects they can have on the human visuomotor system. For example, without appropriate matching to the distance of the work, stereoscopic Augmented Reality headsets will or can lead to eye strain and impair a maintainer's ability to assess distance. Differences in onboard cameras can degrade an Augmented Reality platform's ability to present relevant details in the visual field and lead to misleading assessments of task performance. Obtaining optimal value and benefits from investments in this technology requires consideration of the unique characteristics of each combination of platform, use environment, use case, and the content that will be presented. Our paper will present guidelines to consider when purchasing Augmented Reality solutions to help potential users determine appropriate maintenance-based use-cases and estimate the return on investment from purchases of augmented reality technology. In the paper, which is follow-on work to a paper presented at I/ITSEC 2022, we will explore the types of platforms used to drive visual augmented reality, how these platforms integrate with the human visuomotor system, how hardware limitations limit the capabilities of a platform, and rules of thumb to define platform requirements based on the use case.

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The potential of Augmented Reality (AR) to support maintenance has been considered and investigated for over 50 years. Recent advances in commercially available AR hardware platforms offer increased potential to insert information into a maintainer's visual field. Camera-equipped AR headsets can send imagery to a remote collaborator who can provide the user with verification, oversight, and assistance and provide analysis about what the AR user could see. AR enhancements range from intuitive access to digital documentation, supporting increased time-on-task to real-time computer-assisted visual assessments that reduce maintainer cognitive load and likelihood of errors. However, AR platforms vary drastically in terms of capabilities and potential effects on the human visuomotor system. Without appropriate matching to the distance of the work, stereoscopic AR headsets can lead to eye strain and impair a maintainer's ability to assess distance. Differences in onboard cameras can degrade an AR platform's ability to present task-relevant details in the visual field, leading to misleading assessments of task performance. Obtaining optimal benefits and return on investment from this technology requires consideration of the unique characteristics of each combination of platform, use environment, use case, and the content that will be presented. We present guidelines to consider when purchasing AR technology to help potential users determine appropriate maintenance-based use-cases and estimate the return on investment from AR technology purchases. Our paper is follow-on work to a paper presented at I/ITSEC 2022 to further explore types of platforms used to drive visual augmented reality, how these platforms integrate with the human visuomotor system, how hardware limitations limit the capabilities of a platform, and rules of thumb to define platform requirements based on the use case. We begin with an overview of common pain points encountered by maintainers and will organize them into a number of high-level categorical groupings.

Historical Uses of AR in Maintenance

Historically, technical instructions about how to perform maintenance have been provided through paper manuals. As an example, Air Force Technical Order 00-5-1, *AF Technical Order System* (2016) lists approximately 30 type-categories of publications and support data documents. These documents can provide a variety of types of instructions that range from operating specific hand tools to flying combat aircraft. As examples categories of types of technical orders include operations and maintenance of major weapons systems; general methods and procedures; on-equipment maintenance procedures; task work packages; and inspection cards and checklists).

As technology is being fielded, AR systems have become available for applications to maintenance work. Feasible systems must meet several requirements. Because the work can expose them to temperature extremes and humidity, they need to be resistant to moisture and work across a wide range of temperatures, from sub-freezing to extremely hot. Systems need to be sufficiently rugged to survive rough handling in dirty environments. They may need to meet specific safety requirements, such as to be compatible with safety eyewear and other protective equipment and be approved for use in explosive atmospheres, Processors need to be sufficiently low weight and compact to minimize the load the maintainer must carry and wear, while also having adequate battery life. To date, most available AR systems project text or icons into the user multimedia or screen.

Contemporary Challenges in Maintenance

Maintainers are largely Air Force enlisted members. Most enter the Air Force shortly after high school graduation, although many have completed some college courses. After completing basic military training, enlisted members attend technical schools to prepare them to perform in their assigned career field. These courses are typically delivered as group lockstep and assume trainability but no prior experience in the course content. The length of training varies depending on the complexity of the career field, with some technical schools lasting several weeks and others lasting just short of one year. The Air Force Community College enables enlisted Air Force members to complete associates (2-year) degrees related to their technical training and partially based on expertise acquired through Air Force training and experience. Following technical school, every Air Force member is enrolled into a locally administered on-the-job training program that expands on the competencies acquired in technical school, providing additional depth that is tailored toward performing the duties needed at that location. A document called the Career field education and training plan, or CFETP, is available for every enlisted military specialty. CFETPs describe career-long progression through the career field, recommend or mandate training opportunities, describe responsibilities at the different levels of military rank and position, and include a Specialty Training Standard that outlines all the tasks to be performed as knowledge about the task and related levels of knowledge and skills. Although senior noncommissioned officers supervise and lead most maintenance activities, officers are assigned to higher levels to provide oversight and senior leadership and management. In some situations, the Air Force employs civilian members in maintenance roles, typically in locations that are unlikely to involve direct combat activities. Air Force maintainers may also interact with civilian employees of companies furnishing weapons systems. These technical representatives provide a bridge between Air Force maintainers and the manufacturer's engineering staff to manage long-term trends and resolve the rare issues for which approved technical procedures do not exist.

Maintenance actions are governed by the content of Air Force Technical Orders (TOs). Air Force personnel are required to use and refer to prescribed technical information to perform aircraft and equipment maintenance and must comply with the procedures described within these information sources (AFI 21-101, 2020, para 1.6.2.). This should also satisfy the requirement that before starting any task, the task performers must review the applicable technical orders to familiarize themselves with the procedure and ensure they are using the most recent procedure (AFTO 00-5-1, 2016, para 1.5.). Typically, the relevant TOs will be near at hand for ready reference while performing procedures. To date, TOs have primarily been paper based, however, they are now available as pdf electronic copies. The tasks maintainers perform range across inspection, servicing, removal and replacements of parts and subassemblies, and major maintenance on complete aircraft that removes and replaces engines, landing gear assemblies, and avionics systems. They also operate a variety of powered and unpowered support equipment including lifting jacks, work stands, ground power units, and portable lighting. Maintenance jobs use bomb lift equipment and delivery trailers to move munitions and operate K-loaders that move pallets of cargo. The purpose for some maintenance specialties is to repair equipment other maintainers use on the flight line, others inspect, maintain, and repair components in work areas that are removed from the immediate vicinity of aircraft operations.

Instructional Tracking

Appropriate technical orders are required to be immediately available for ready reference at work sites. Challenges in using these paper manuals that are driving AR alternatives include the administrative effort to curate libraries of publications; the weight and volume required to have printed materials available at work sites; challenges of using paper manuals in bad weather, night, and within confined spaces. A specific task may require the maintainer to cross-reference multiple printed sources, such as the manual to operate a torque wrench and the system maintenance guide that sets the required torque value for a fastener. Procedures become more cognitively challenging when subordinate commands add additional (supplementary) instructions.

Because they are printed materials, there are limitations in how technical publications can convey information. They require the maintainer to apply cognitive effort to translate words and illustrations to planned behaviors,

recall the behaviors in conscious memory, and then perform the behaviors. Printed materials have difficulty depicting motion and weight, showing how parts fit together, or providing 360-degree perspectives.

Ideally, AR systems could display just-in-time maintenance instructions in a user's eyepiece. Integrated instructions would blend all needed content into a single stream, eliminating the need to switch across different sources. The AR eyepiece would be less cumbersome to use than stacks of printed materials, display information as needed, and free the user's hands for task work.

Visual inspection

Maintainers are frequently tasked with the visual inspection of physical systems (such as aircraft panels and wiring systems). During these inspections they will inspect the physical system for signs of wear, or other symptoms that would indicate that component replacement and/or repair are necessary (signs of corrosion, rust, or chafing). What can make this task difficult for a maintainer, is the variety of physical components that require inspection, and the quantity of components that can require inspection. Studies show that maintainers are less likely to use their checklists for daily tasks, because they are too time consuming, and an expectation that more experienced maintainers will remember the common procedures executed daily. Consequently, the study found that one of the most common errors on a flight line were associated with areas of the aircraft not being checked for damage (Langer & Braithwaite, 2016). When executing a large number of inspections for problems that occur rarely, the individual becomes at risk of change blindness, a state where one's expectations for what they will see can lead to them failing to recognize the "odd one out" when it eventually arrives (Mancero et al., 2007). Ideally, an AR system would assist the maintainer in these inspections, acting as a second pair of eyes, alerting them to signs of wear or damage the maintainer may have missed.

Identifying non-visual error states

Maintainers responsible for the assembly and repair of component rely on large-scale industrial machinery to execute that work. This industrial machinery also needs to be monitored and repaired. However, complex industrial machinery may have faults that cannot be identified through visual inspection, and may instead require the maintainer to monitor sensors that relay information on the health of the machinery, then to apply their knowledge of the system's usage history, and it's frequency of maintenance, to discern whether the machinery is near a state of failure, and would require a closer inspection or for the maintainer to place an order for replacement parts. Ideally, an AR system would continuously monitor the health of the machinery in the facility and would alert a maintainer if these systems expressed signs of abnormality.

Procedure Validation

The procedures required to maintain or repair a physical system will vary dependent on several factors (including the underlying state of the system, the location of the procedure, OEM specifications, battlespace conditions). Although applying an incorrect corrective procedure to a problem may still resolve an immediate need, it could lead to unforeseen repercussions in the future. For example, improperly closed door panels, and latches have been known to result in serious cost or damage (Langer & Braithwaite, 2016). Ideally, an AR system would be able to double check and validate the work that was done by a maintainer, so that it could provide early alerting if it noted a mistake.

Classifying Maintenance Challenges

Tasks required of maintainers are rapidly dynamic and will continue to grow as the DoD acquires new technology and continues to expand the tactics employed to safeguard the United States. However, categories of discussed in this study, instructional tracking, visual inspection, identifying non-visual error states, and procedure validation are high-level common tasks that can act as the constituent sub-tasks of a more explicit task order. In the next section, this paper will discuss the types of techniques and workflows used in AR system that can be applied towards mitigating pain points associated with these task categories.

Advantages of Augmented Reality

In the last decade, advances in the technical domain drastically increased the feasibility of consumer grade AR systems for operational applications. These advances, reduction in the size and power consumption of displays, development of projection methods that enhance visual comfort, and a miniaturization of processors all contribute to reduced costs and increased accessibility of AR systems (Osborne & Mavers, 2019; Yin et al., 2021). Consumer off the shelf (COTS) AR systems are either incorporated into a cellphone/tablet or use a head-mounted-display (HMD). Collectively, cellphone/tablet-based AR applications are referred to as Mobile Augmented Reality (MAR). MAR applications are highly portable and are installed on a device that maintainers would have with them daily, such as a phone or tablet. In contrast, HMDs are hands-free solutions that the user wears on his or her face.

Functional differences between MAR and AR HMD solutions include user experience and the visual display. MAR solutions are hand-held devices while AR HMDs are hands-free devices worn on the head, enabling users to use the AR HMD without breaking their hands-on workflow. MAR devices are monocular while AR HMDs which are stereoscopic. Then MAR device typically uses a monocular solution that presents a 2D image on a flat screen to one eye. A stereoscopic AR HMD displays a different image to each eye, enabling the system to emulate a sense of depth. The systems differ in sensor placement. Because AR HMDs are head-mounted, the AR HMDs onboard sensors can directly interact with the user's visual and auditory senses. For example, the Microsoft HoloLens has eye-tracking that enables the AR HMD to identify where the user is looking and leverage that information to alter the display.

Contemporary MAR and AR HMDs are all supported by mobile processors commonly used in cellphones (such as the Snapdragon family of processors by Qualcomm). However, while these mobile processors themselves have seen exponential growth, with the reduced latency of modern Wi-Fi, processing is no longer limited to the AR system itself, and can be executed on an external computer (referred to as "edge computing") or on a cloud service. This increase in computational capability enables modern AR systems to leverage vision processing algorithms that were previously infeasible, and to use input from Internet of Things (IoT) and environmental sensors (Parida et al., 2021; Park et al., 2019). An example of how access to increased processing power and IoT sensor connectivity can enhance the capability of AR systems is the X-AR system developed by MIT. X-AR connects an AR HMD to sensors and cameras placed throughout a facility, enabling users to "see-through walls." In the following sections, this paper will examine some of the capabilities these advances enable and the benefits they can bring to maintainers. These sections will also explore the risks inherent in the use of the capabilities, that can impair a maintainer's efficiency, accuracy, and cognitive performance. We next focus on how some of the techniques and workflows can be integrated into contemporary AR systems (Boroushaki et al., 2023) and what users should consider before purchasing these systems.

Considerations in Using Augmented Reality

AR systems have significant promise in their ability to assist maintainers in their workflow, and AR HMDs enable users to see 3D holograms and visualizations superimposed on real-world environments. However, fully informed users should consider how the process of emulating stereoscopic 3D vision can result in temporary side-effects to the human visuo-perceptual system. Furthermore, the hardware powering the AR system itself will constrain the performance of the

system, restricting the operational usage of the AR system. The goal of this section of the paper is to: (1) highlight the constraints of AR systems, and how they can affect a user's visuo-perceptual system, and (2) discuss how to account for these constraints when selecting an AR system to optimize the value for your use-case. These risks and concerns include inappropriate visual overlays, nuanced function of object recognition and tracking, inaccuracies in digital assistants, differences in how human visual processing interacts differently with AR technology and the real world, and hardware constraints.

Visual overlays

Maintainers use documentation and manuals in their daily work as technical references to execute work procedures and to record progress and work executed. Maintainers risk procedural errors if steps are not properly followed; documentation errors for failures in logging and issue tracking; and communication errors if critical information is not relayed between maintainers (Langer & Braithwaite, 2016). Augmented Reality systems can streamline the process of accessing reference documentation, display reference information in real-time, and record information provided by the maintainer to automate the logging process. This reduces the risk of error inherent in manually searching through reference documentation and the time to document (log) accomplishment of tasks and remaining issues. For these reasons, AR systems can provide significant benefit towards execution of procedural tasks that require reference material. Furthermore, studies show that having an overlay with reference material available when executing procedural tasks will reduce cognitive load, reducing the likelihood of attentional errors.

Conversely, studies also show that the use of an AR system to assist with reference material for procedural tasks will cause users to develop a reliance on the AR system. When using an AR system that displays reference material as needed, users do not need to store this material in their memory for longer than seconds at a time and are not required to process the information as deeply. Studies suggest this can diminish a user's understanding of the underlying information and can degrade their ability to extend their skills to novel environments when not aided by the AR system (Radu, 2014; Rehman & Cao, 2019).

This degradation in knowledge retention can be mitigated through focused design that incorporates learning methodologies (Moghaddam et al., 2021). This learning-facilitation design reduces the potential that AR system overlays of reference material will build overreliance on the system rather than learning the content. Furthermore, MAR and AR HMDs should be used for different use-cases. MAR solutions can enable maintainers to access reference material using a hand-held device. AR HMDs can display reference material in front of their eyes, effectively enabling them to work with their hands while looking at the associated reference material. However, overlaid visual information can obscure critical real-world visual information. AR HMDs will also obscure a maintainer's visual perceptual capability, eliciting effects such an impairing their ability to judge and estimate distances and can result in negative physiological effects such as eyestrain over time. When evaluating an Augmented Reality system to visualize reference information, the following factors should be considered: (1) The risks associated with maintainers becoming over reliant on the AR system; (2) Whether the AR system would disturb existing workflow of maintainers; (3) Whether the potential physiological side-effects of the AR system would endanger the work.

Object Recognition and Tracking

To support visual inspections, in which maintainers visually assess the health of wiring and other physical components, AR systems equipped with cameras and other supporting sensors can leverage computer vision to augment the AR system's understanding of the world. Computer vision is a research domain that enables computer systems to use cameras to understand visual characteristics of the world. For a computer, an image is a matrix of pixels. A pixel is a single illuminated point. In the example shown in Figure 1, an image consists of a matrix of black, gray, and white pixels. To enable a computer system to understand the world, a computer vision first maps this matrix of pixels, into higher-level patterns and shapes (called features). These features can then be mapped to higher-level concepts such as objects. These objects can then be recognized, tracked, and evaluated. The general pipeline for computer vision algorithms is: (1) mapping pixels to features (feature extraction); (2) mapping features to objects/higher-order concepts (classification); and (3) executing analysis on these objects (analysis). This is important because a failure in any of these steps can substantially degrade the accuracy of the results, leading to a product that is brittle and unreliable. Computer Vision systems are notorious for being situationally accurate, meaning that they work perfectly for one situation and fail catastrophically in another (Andreopoulos & Tsotsos, 2013). As a result, an AR system leveraging computer vision can work well in one environment but fail when moved in a different environment.

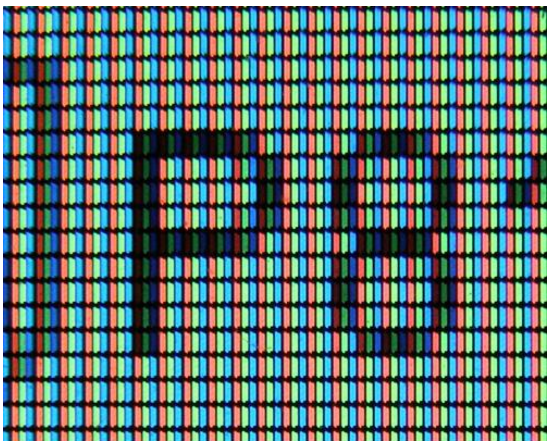

Figure 1. Close-up of image of the characters "P8" on an LCD display from "Pixel", by Kprateek88 (2008), (https://en.wikipedia.org/wiki/Pixel). GDL and CC-BY-SA

Feature extraction is vulnerable to changes in an operational environment because it can change the pixels in an image. Specific conditions in that can impair feature extraction include occlusion (in which other objects are between a target object and camera), dirt and grime, changes in lighting conditions and/or shadows, and the presence of clutter. To highlight how environmental conditions can affect computer vision, Figure 2 is a picture of a rock under three viewing conditions. Figure 2(a) is the rock on a clear day, Figure 2(b) is the rock at sunset, and Figure 2(c) is the rock after moss has grown on it. A human can easily assess that the same rock is shown under different conditions. However, a feature extraction algorithm must first extract features from the pixel matrix of the image. Next to each picture of a rock, is a close-up of a region of the rock to demonstrate the difficulty a feature extraction algorithm could have with these images. Because of the sunset, (b) has a non-significant orange tint added to the rock. Whereas (c) has moss added to it, which can add new patterns to the image, that can obfuscate the ability of a classification algorithm to identify the rock, if it was only trained on a rock without moss. The data used for training are critical because they provide the means by which the algorithm matches an identification of an object to the pattern of pixels in an image. In one example, an

Figure 2. Rock under multiple viewing conditions: (a) is on a clear day, (b) is at sunset, and (c) is after moss has grown on it

algorithm had learned that yellow identified busses. It identified yellow-colored armored tracked fighting vehicles as busses but could not identify busses that had been painted other colors.

Innovations in computer vision frequently cannot be quickly adapted to maintenance environments, which can feature clutter, dynamic lighting conditions, and where wires and other hardware can be scuffed, or have oil or grease on them, which can change the visual characteristics of the object for analysis. Many of these environmental difficulties can be mitigated by adding sensors. Depth cameras can enable computer vision systems to leverage geometric information that increases resilience against lighting or shadowing conditions or add information about variances the environment. When physical dimensions of all components in a maintenance environment are known, this information can help mitigate issues related to occlusion or changes in lighting conditions. However, these are all conditions that must be mitigated. As such, when evaluating the applicability of an AR system that incorporates computer vision for a maintenance environment, it is important to either: (a) Understand what environmental challenges exist in the operational environment and how the proposed system will mitigate them, or (b) Ensure that the proposed AR system to tested in a representative environment that replicates the same challenges encountered in the target maintenance environment, to ensure the AR system is built with the propre mitigations in mind.

Digital Assistants

As Augmented Reality systems gain access to greater computing resources and the sensors used to monitor our facilities, they become capable of acting as digital assistants. An example set of the capabilities these assistants can embody include systems that automatically walk the maintainer through stepwise procedures and determine the next step by monitoring the maintainer's work, provide warning and alerting of abnormal or dangerous conditions (as determined by monitoring sensor systems), and validate a maintainer's work by assessing the condition of the maintenance environment. The core of these digital assistants is the ability to make proactive decisions and to present results of these decisions to the maintainer. However, digital assistants are not always accurate, and a breakdown in trust between a maintainer and a digital assistant could have hazardous repercussions. One of the most well-known failures in human-machine trust is the use-case of Tesla's autopilot system. Initially, Tesla aired an ad for the Tesla that demonstrated that the vehicles autopilot system could pilot the car for you. Unfortunately, this ad represented "what the vehicle could do in the future" rather than "what it can actually do now," leading potential buyers to set excessive expectations for the autopilot system (Ivanova, 2023; Rice, 2019). Driver misunderstanding of the capability of autopilot systems, can result in trusting them in situations where the technology is not reliable, as exemplified by the 2016 Tesla autopilot accident, where a Tesla's computer vision system mistook a large white truck in front of the vehicle for the sky, and subsequently accelerated into the truck while the driver was watching a movie, believing the system did not need supervision (Ganesh, 2017). A recent study on the misuse of tesla's autopilot system surveyed 103 tesla drivers who use autopilot on a regular basis. They found that 46.6% of the drivers used the autopilot system outside of its operational design domain (i.e., situations in which the system is approved for usage), either due to lack of knowledge and/or over trust in the technology's competence. Similarly, 44.6% of the drivers reported an increase in time with their eyes off the road, or executing secondary tasks such as working from their laptop while driving. (Nordhoff et al., 2023).

Trust calibration is the process of calibrating a user's expectations of when they can trust an automated assistant and training them to understand how the assistant can fail. Without proper trust calibration, users are at risk of either under or over-trusting the assistant. If a user trusts the assistant, then the user will not use the assistant, effectively wasting the acquisition a waste of time and money. However, if the user over trusts the assistant, that means they can be working from inaccurate information, potentially missing a critical alert that the assistant has not given them, putting themselves and others at risk. Currently, the only method that AR user actions could be monitored for completeness and correctness is through a camera installed into the AR headset, enabling what the user is seeing to be monitored remotely, coupled with a remote display of information being provided to the AR user. However, we note that this would be an improvement over current practice where managers and quality assurance inspectors can, at best, be on-site to watch the work being performed or check work progress at specified points or when completed. These methods are typical and in

common use today. The use of cameras to monitor work would not be only a technology question, as organizations will need to establish processes for performing the remote inspections and determine how, when, and for how long work will be monitored.

The problem with misaligned trust in automation is not that the assistant is not always correct, but rather that the user does not have enough information to make an informed decision. There is a particularly high onus on Augmented Reality systems deployed to maintenance environments to properly calibrate trust. Because mistakes in a maintenance environment can occur down the line, when the equipment that was maintained suffers a failure during operational usage.

One approach to trust alignment is the use of explainable AI, which are methodologies characterize the decision-making workflows of AI-driven systems. This allows users to trace how the digital assistant made its decisions, enabling users to trace and assess the validity of the digital assistant's decision making workflows (Angelov et al., 2021; Tsiakas & Murray-Rust, 2022) , in which digital assistants express to users when they are uncertain about a decision and ask the human-user to resolve the ambiguity. For example, if a computer vision integrated digital assistant is unable to assess whether a component it is inspecting is in good health or not, it can ask a maintainer to verify whether the component is in need of repair.

When evaluating the applicability of Augmented Reality digital assistant as a solution to a maintenance environment, the key takeaway that must be evaluated is the *transparency of the Augmented Reality system's decision-making process*. It is critical that a maintainer must understand the reason behind the decisions made by a digital assistant, and that there is evidence the maintainer to reference to validate the digital assistant's decisions. This is particularly relevant given the increased prevalence of Deep Learning convolutional neural networks of Large Language Models (LLMs), which leverage statistical methods to predict the most likely outcome, given a set of input data. The accuracy of these models is dependent on the data on which they were trained, consequently, these models may be accurate in one setting, and unreliable in another. For example, facial identification algorithms are notoriously bad at identifying the faces of non-Caucasian individuals because these systems were predominantly trained on Caucasian faces (Coe & Atay, 2021). If a system lacks transparency, and cannot explain the reason for its decisions, in a way that can be validated by a maintainer, there is an inherent risk of the digital assistance encountering an unknown situation, where its accuracy will degrade, without the maintainer's awareness.

Physiological Impact of Augmented Reality

When an individual uses both of their eyes to focus on an object, it triggers a reflex called the Vergence-Accommodation reflex. This is a process in which both eyes rotate to look at the object, then the lenses of both eyes alter their shape to focus based on the distance to the object. The problem arises from AR HMDs simulating holograms being in the distance by projecting different images to both eyes, but the holograms will always be displayed on the HMDs lens, which is a set distance from the user's eyes. This process is shown in Figure 3. Figure 3(a) shows two eyes focusing on a real-world object, where the eyes rotate to center on the object, and the lens of each eye adjusts itself based on the distance to the focal object. Figure 3(b) shows two eyes focusing on an object that is displayed on the lens of the AR HMD (the lens of the AR HMD is the center line in Figure 3(b). In this example, the eyes rotate to center on where the object is believed to be, but the lens of each eye, adjusts itself based on the distance from the eye to the lens, instead of the location where the AR HMD has projected the object. Because the holograms can appear as-if they're moving closer and further from the user, but their actual distance never changes, the lenses of the eyes do not need to adjust themselves the same way they would for a real-world object that is moving closer or further away.

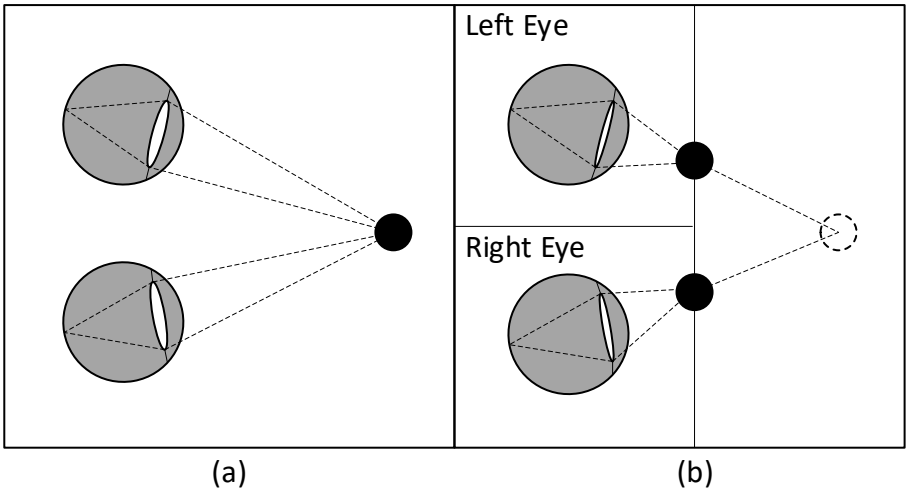

Figure 3: A side-by-side of (a) two eyes focusing on an object in the real-world and (b) two eyes focusing on an object displayed to the lens of an AR HMD

This conflict between two sources of distance information interferes with the eyes' Vergence-Accommodation reflex and puts the user's eyes in a state called Vergence-Accommodation Conflict (VAC). During this conflict, the eyes temporarily decouple the Vergence-Accommodation reflex. VAC is extremely stressful for the ocular system, and the longer a user is under VAC conditions, the more severe their symptoms will grow. Some of the more prohibitive symptoms of VAC are eyestrain, headaches, and impaired decision-making. Although the strength of VAC symptoms can be delayed mitigated with intelligent software design, if a user wears an AR HMD long enough, then these symptoms will occur. There is active research on the design of experimental lenses to mitigate VAC symptoms in the near future (Zhou et al., 2021), but these lenses have yet to reach commercial viability. More detail about VAC, as well as software design methodologies to mitigate these symptoms are discussed in the author's previous report (Flowers & Rebensky, 2022).

A second known effect of AR systems on visual perception, is a degradation in spatial perception, which is their ability to assess the distance to and size of objects around them. This is particularly true when assessing holograms, which can lack many of the visual cues of real-world objects, such as shadows. When referencing the impact of AR systems on spatial perception, we refer to depth as one of three visual fields: (1) near field, when looking at objects with 2 meters of the user; (2) medium field, when looking at objects between 2-30 meters from the user; and (3) far field, for objects greater than 30m from the user. When working in the near-field, AR systems will cause users to overestimate the distance to objects, leading them to believe that objects are further away from them than they are. In the medium and far-field, users will underestimate the distance to objects, believing them to be closer than they are (Jamiy, 2019; Jamiy & Marsh, 2019; Khan et al., 2021).

To better understand the effect AR systems can have on spatial perception, it is important to further characterize AR HMDs into two categories, video see-through (VST) and optical see-through (OST). A VST AR HMDs is fully enclosed and uses cameras mounted on the HMD to display the real-world outside the headset to users. Effectively, when using a VST AR HMD, the user is looking at a live video of the real world. COTS examples of VST AR HMDs are the Meta Quest Pro and Vive XR Elite headsets. Whereas OST AR HMD put a clear lens in front of the eyes that enable the users to see the real-world when looking through it, and holograms are projected on top of the lens, so that it appears that a hologram has been inserted into the real-world. COTS examples of OST AR HMDs are the Microsoft HoloLens and the MagicLeap 2 (Peillard et al., 2020).

A comparative study found that the severity of depth misestimation is dependent on the distance to the object the user at and the type of AR system in-use. When looking at objects in the medium field (2 to 30 meters), on average, an OST AR HMD will cause users to underestimate the distance to an object by approximately 15%. Whereas VST AR HMD, will cause users to underestimate distance by approximately 20% (Adam et al., 2022). MAR will also affect a user's spatial perception, but the granularity of this effect for MAR is less well

characterized than for AR HMDs. Studies suggest that users can adapt to work with degraded spatial perception, particular for OST AR HMDs (which are better studied), that this degradation can be mitigated with careful software design (such as by adding missing environmental cues like shadows; Adam et al., 2022; Martin-Gomez et al., 2022). Future lens designs under study further diminish this issue (Peillard et al., 2020), but caution should still be applied when considering AR solutions for precise and/or volatile work.

Hardware Constraints

The underlying hardware powering an AR Systems will dictate its capabilities and the types of environments it can be used in. Specifically, OST AR HMDs, particularly those using waveguide optical combiners, use light to project holograms on top of the clear lens in front of the user's eyes. This effectively combines the light the user sees from the real-world with the light from the hologram, seamlessly fusing the hologram into the real-world scene. This approach enables OST AR HMDs to realistically add holograms to the real-world, but there are two repercussions of this approach: (1) the color displayed to users is effectively a *blending* of the light of the real-world and the light of the project, as a result, it is not feasible to display exact colors on OST AR HMDs (because all colors displayed will be offset by the light from the real-world), in the worst case, depending on what is behind the HMDs, some colors could be rendered invisible and bleed into the background (Erickson et al., 2022); and OST AR HMDs are highly vulnerable strong lights (such as direct sunlight), which can overpower the projection mechanism (Erickson et al., 2020). To mitigate this issue, many OST AR HMDs use tinted visors. Furthermore, the projectors used in traditional OST AR HMDs are unable to accurately represent the color black. There are three implications of these factors: (1) OST AR HMDs can have poor performance within certain lighting conditions; (2) due to optical noise (variance in external lighting conditions), and OST AR HMDs cannot accurately represent granular colors.

A relevant example of these physiological and hardware induce impairments can harm operational efficacy is the Microsoft IVAS. IVAS is a successor to the Microsoft Hololens 2 OST AR HMD that designed for a military audience. During field testing last year, warfighters expressed concern that the device resulted in eyestrain, headaches, and had extremely poor visibility in low-light conditions. This resulted in a significant cut to funding for the IVAS program, and concern about the viability of the AR HMD's deployment (Roque, 2023).

When determining the applicability of an AR solution, beyond the technical capability of the device to meet the needs of the problem, both the effect the device will have on maintainers, and whether the device will interfere with the operation must be considered. While these concerns can be mitigated through use-case focused design, it is important to consider:

1. When using an AR HMD, the longer the device is in use per session, the higher the likelihood that maintainers will develop VAC-induced symptoms (often eye strain, fatigue, and headaches). Symptoms will grow progressively more severe the longer the device is in use without a break.

2. AR systems can have a minor effect on the ability of maintainers to judge distances. This effect is smaller for OST AR HMDs compared to VST AR HMDs.

3. OST AR HMDs can have reduced visibility within device-specific lighting conditions and are unable to represent granular variance in color due to optical noise.

Application Mapping

This paper reviews how contemporary AR methodologies can assist maintainers, provides information that can be used when assessing whether an AR solution meets the requirements of the problem space, and the risks associated with the hardware platforms used by the contemporary AR systems. To assist in the process of determining what category of AR system would meet the needs of the problem space, Figure 4 is a decision tree that discusses what AR methodologies and hardware platform are a good fit for a maintainer's problem space.

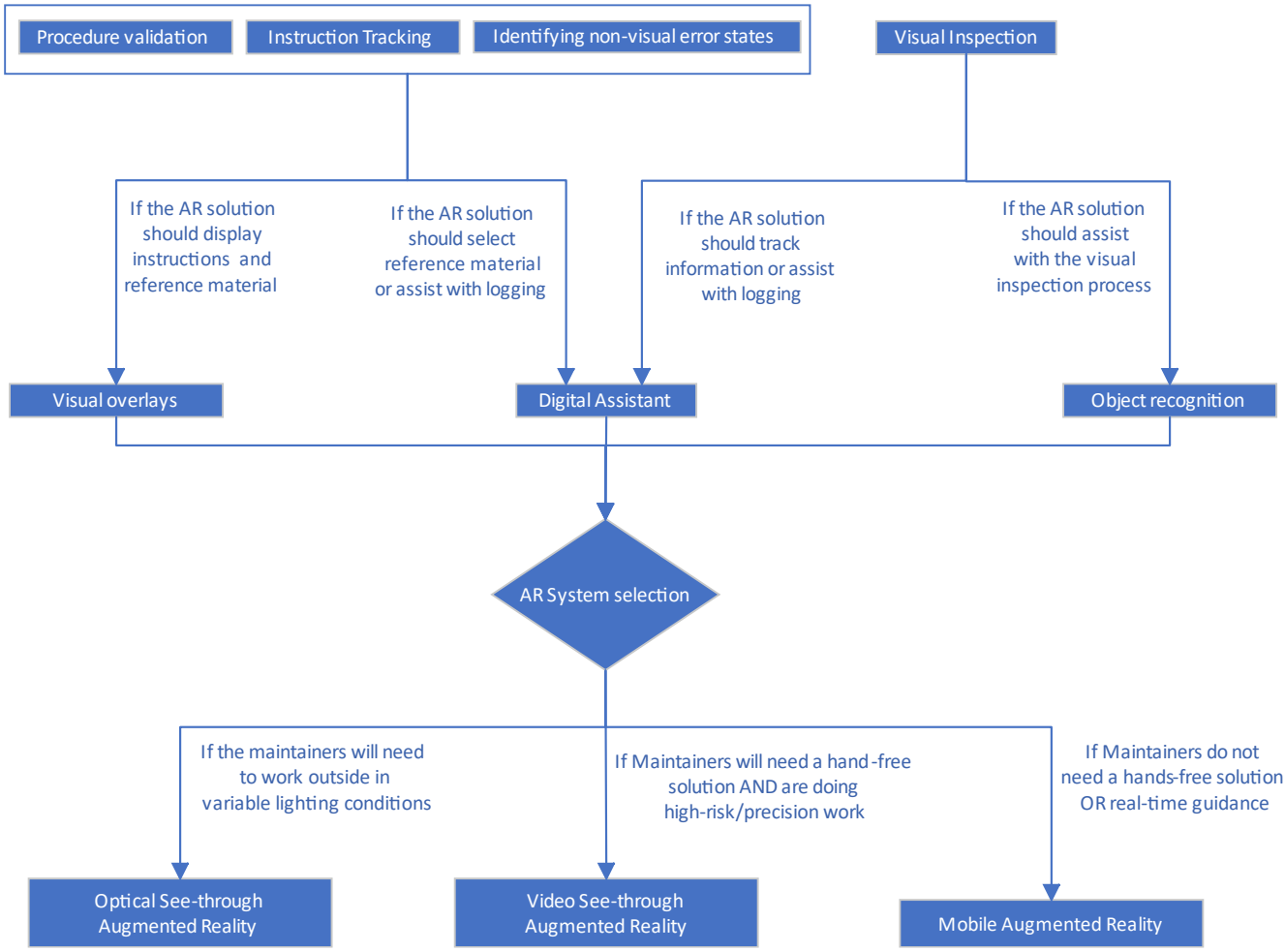

Figure 4: Technology selection decision tree

After identification and selection of an AR system leveraging the required methodologies for the problem space, how well the proposed AR solution will meet the needs of the operational environment must be assessed. The questions that must be answered for this assessment are summarized in Table 1.

Table 1: Solution fit mapping

Visual overlays	Object tracking	Digital Assistant
Is there a risk of maintainers becoming over reliant on the AR system?	What environmental challenges exist in the operational environment, and how the proposed system will mitigate them?	Is there transparency in the AR system's decision-making process?
Will the user experience disturb the maintainers existing workflow?	Will the proposed AR system be tested in a representative environment with the same challenges?	

Visual overlays	Object tracking	Digital Assistant
Will the associated physiological side-effects of the chosen system endanger the work?		

Then, a risk characterization for the usage of the hardware itself should be executed, to ensure that the risks associated with the solution, do not exceed the potential benefit. Table 2 summarizes risks and physiological side-effects associated with usage of AR hardware platforms.

Table 2: AR Hardware platform risk characterization

Hardware	VAC-symptoms (eyestrain)	Degraded spatial perception	Light-limited usage	Degraded contrast perception
Mobile Augmented Reality		✓		
Video See-through HMD	✓	✓		
Optical See-through HMD	✓	✓	✓	✓

Conclusion

The current state of augmented reality offers many exciting possibilities for military maintainers. Augmented reality has the potential to provide more detailed information, tailored specifically to meets of the individual maintainer in terms of level of detail, depth, timeliness, and as integrated procedures in a hands-free mode at the work site. However, fulfillment of this vision will require users and developers to determine appropriate and sufficiently detailed maintenance-based use-cases and to be empowered to make better purchasing decisions based on accurate estimates of the return on investment from purchases of augmented reality technology. In a previous paper by the authors, we discussed our methodology for determining requirements when modernizing training to optimize effectiveness (Rizzardo et al., 2022). In this paper, we have discussed the current benefits and limitations of the state-of-the art AR technology. Instead of viewing AR technology as a simple and a ready for use, off the shelf purchase, adapters of AR technology need to understand the capabilities of current hardware and the larger challenge of developing the information systems that will produce the content that the hardware will display. The principles of socio-technical systems theory (Abbas & Michael, 2023) posit that organizational functioning is based on the expertise of members, the work they perform, and the technology, leadership, and managerial practices that organize work tasks and direct their performance. AR will be a change to how maintenance tasks are performed and how the work is managed. Full benefit from properly planned and implemented investments in AR technology will greatly enable maintainers to deliver optimally performing technology to military warfighters.

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References

Abbas, R. & Michael, K. (2023) Socio-Technical Theory: A review. In S. Papagiannidis (Ed), *TheoryHub Book*. Available at http://open.ncl.ac.uk / ISBN: 9781739604400

Adam, H., Steffanucci, J., Creem-Regehr, S., & Bodenheimer, B. (2022, March 12). Depth Perception in Augmented Reality: The Effects of Display, Shadow, and Position. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. https://www.researchgate.net/profile/Haley-Adams-8/publication/360100271_Depth_Perception_in_Augmented_Reality_The_Effects_of_Display_Shadow_and_Position/links/62695f0b05d79a3968a5f75a/Depth-Perception-in-Augmented-Reality-The-Effects-of-Display-Shadow-and-Position.pdf

Andreopoulos, A., & Tsotsos, J. (2013). 50 Years of Object Recognition: Directions Forward. *Computer Vision and Image Understanding*, *117*(8), 827–891.

Angelov, P., Soares, E., Jiang, R., Arnold, N., & Atkinson, P. (2021). Explainable artificial intelligence: An analytical review. *WIREs Data Mining and Knowledge Discovery*, *11*(e1424).

Boroushaki, T., Lam, M., Dodds, L., Eid, A., & Adib, F. (2023, April 17). Augmenting Augmented Reality with Non-Line-of-Sight Perception. *20th USENIX Symposium on Networked Systems Design and Implementation (NSDI 23)*.

Coe, J., & Atay, M. (2021). Evaluating Impact of Race in Facial Recognition across Machine Learning and Deep Learning Algorithms. *Computers*, *10*(113).

Department of the Air Force Instruction 21-101 DAFGM 2022-01, (2022 8 Nov). Aircraft and Equipment Maintenance Management. Available at https://static.e-publishing.af.mil/production/1/af_a4/publication/dafi21-101/dafi21-101_dafgm2022-01.pdf

Erickson, A., Kim, K., Bruder, G., & Welch, G. (2020). Exploring the Limitations of Environment Lighting on Optical See-Through Head-Mounted Displays. *SUI '20: Proceedings of the 2020 ACM Symposium on Spatial User Interaction*, 1–8.

Erickson, A., Kim, K., Bruder, G., & Welch, G. (2022, January). *A Review of Visual Perception Research in Optical See-Through Augmented Reality*. International Conference on Artificial Reality and Telexistence Eurographics Symposium on Virtual Environments (2020), Online.

Flowers, B. A., & Rebensky, S. (2022). Are you seeing what I'm Seeing?: Perceptual Issues with Digital Twins in Virtual Reality. *IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 126–130.

Ganesh, M. (2017). ENTANGLEMENT: MACHINE LEARNING AND HUMAN ETHICS IN DRIVER-LESS CAR CRASHES. *A Peer Reviewed Journal About*, *6*(1), 77–87.

Ivanova, I. (2023, January 17). Tesla engineer says company faked "full autopilot" video: Report. *CBS News*. https://www.cbsnews.com/news/tesla-autopilot-staged-engineer-says-company-faked-full-autopilot/

Jamiy, F. (2019). Survey on depth perception in head mounted displays: Distance estimation in virtual reality, augmented reality, and mixed reality. *IET Image Processing*, *13*(5), 707–712.

Jamiy, F., & Marsh, R. (2019). Distance Estimation In Virtual Reality And Augmented Reality: A Survey. *2019 IEEE International Conference on Electro Information Technology (EIT)*, 63–68.

Khan, F., Muvva, V., & Wu, D. (2021, October 4). Measuring the Perceived Three-Dimensional Location of Virtual Objects in Optical See-Through Augmented Reality. *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*.

Langer, M., & Braithwaite, G. (2016). The Development and Deployment of a Maintenance Operations Safety Survey. *Human Factors*, *58*(7), 986–1006.

Mancero, G., Wong, W., & Amaldi-Trillo, P. (2007). *Looking but not Seeing: Does Perceptual Depth Reduce Change Blindness?* (IDC Technical Report 2007-3–001). European Organization of Aerospace Research and Development (EOARD). https://apps.dtic.mil/sti/pdfs/ADA515539.pdf

Martin-Gomez, A., Weiss, J., Keller, A., Eck, U., Roth, D., & Navab, N. (2022). The Impact of Focus and Context Visualization Techniques on Depth Perception in Optical See-Through Head-Mounted Displays. *IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS*, *28*(12), 4156–4171.

Moghaddam, M., Wilson, N., Modestino, A., Jona, K., & Marsella, S. (2021). Exploring augmented reality for worker assistance versus training. *Advanced Engineering Informatics*, *50*, 101410.

Nordhoff, S., Lee, J., Calvert, S., Berge, S., Hagenzieker, M., & Happee, R. (2023). (Mis-)use of standard Autopilot and Full Self-Driving (FSD) Beta: Results from interviews with users of Tesla's FSD Beta. *Frontiers in Psychology*, *14*. https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1101520/full

Osborne, M., & Mavers, S. (2019). Integrating Augmented Reality in Training and Industrial Applications. *2019 Eighth International Conference on Educational Innovation through Technology (EITT)*, 142–146. https://www.researchgate.net/profile/Scott-Mavers/publication/337790728_Integrating_Augmented_Reality_in_Training_and_Industrial_Applications/links/5dfb82c692851c8364891039/Integrating-Augmented-Reality-in-Training-and-Industrial-Applications.pdf

Parida, K., Bark, H., & Lee, P. (2021). Emerging Thermal Technology Enabled Augmented Reality. *Advanced Functional Materials*, *31*(39). https://onlinelibrary.wiley.com/doi/full/10.1002/adfm.202007952

Park, Y., Yun, S., & Kim, K. (2019). When IoT met Augmented Reality: Visualizing the Source of the Wireless Signal in AR View. *MobiSys '19: Proceedings of the 17th Annual International Conference on Mobile Systems, Applications, and Services*, 117–129.

Peillard, E., Itoh, Y., Normand, J.-M., Sanz, F., Moreau, G., & Lécuyer, A. (2020). Can Retinal Projection Displays Improve Spatial Perception in Augmented Reality? *ISMAR 2020 - 19th IEEE International Symposium on Mixed and Augmented Reality*, 124–133.

Radu, I. (2014). Augmented reality in education: A meta-review and cross-media analysis. *Personal and Ubiquitous Computing*, *18*, 1533–1543.

Rehman, U., & Cao, S. (2019). Comparative Evaluation of Augmented Reality-based Assistance for Procedural Tasks: A Simulated Control Room Study. *Behavior & Information Technology*, *39*(11). https://uwspace.uwaterloo.ca/bitstream/handle/10012/15273/2019-Rehman%20and%20Cao-Accepted%20Manuscript%20[BIT].pdf?sequence=1

Rice, D. (2019). The driverless car and the legal system: Hopes and fears as the courts, regulatory agencies, waymo, tesla, and uber deal with this exciting and terrifying new technology. *Journal of Strategic Innovation and Sustainability*, *14*(1), 134–146.

Rizzardo, C., Rebensky, S., Flowers, B., Reynolds, J., Neubauer, P., & Halverson, K. (2022, December 1). Training Alchemy – Effectively Converting Traditional Training Content to Gold. *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC) 2022*.

Roque, A. (2023, May 10). Last stand for IVAS? New challenges, delays as Army debates future of augmented reality goggles. *Breaking Defense*. https://breakingdefense.com/2023/05/last-stand-for-ivas-new-challenges-delays-as-army-debates-future-of-augmented-reality-goggles/

Tsiakas, K., & Murray-Rust, D. (2022). Using human-in-the-loop and explainable AI to envisage new future work practices. *The15th International Conference on PErvasive Technologies Related to Assistive Environments*, 588–594. https://dl.acm.org/doi/fullHtml/10.1145/3529190.3534779

Yin, K., He, Z., Xiong, J., Zou, J., Li, K., & Wu, S.-T. (2021). Virtual reality and augmented reality displays: Advances and future perspectives. *Journal of Physics: Photonics*, *3*(2). https://iopscience.iop.org/article/10.1088/2515-7647/abf02e

Zhou, Y., Zhang, J., & Fang, F. (2021). Vergence-accommodation conflict in optical see-through display: Review and prospect. *Results in Optics*, *5*, 100160.