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X-RAY VISION: APPLICATION OF AUGMENTED REALITY IN AVIATION MAINTENANCE TO SIMPLIFY TASKS INHIBITED BY OCCLUSION

Mcneely, Justin R.

Monterey, CA; Naval Postgraduate School

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THESIS

X-RAY VISION: APPLICATION OF AUGMENTED REALITY IN AVIATION MAINTENANCE TO SIMPLIFY TASKS INHIBITED BY OCCLUSION

by

Justin R. Mcneely

June 2022

Thesis Advisor:	James J. Fan
Co-Advisor:	Perry L. McDowell

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This thesis examined the potential applications of augmented or mixed reality (AR/MR) technology and leveraging them in the context of the aviation maintenance community. Specifically, we examined whether using the 3D mapping and real-time space tracking technology of devices like the Microsoft HoloLens 2 can be used to make maintenance tasks easier in environments where the maintainer is not able to see into their workspace. With the complexities of aircraft construction, the prevalence of narrow, tight fitting spaces that are blocked by walls or obstructions is common. In the past, aviation maintainers have had to rely on memorizing 2D diagrams and feeling around dark, cramped spaces in order to determine where certain parts are located. Previous research in the field of AR primarily focuses on comparing AR methods to traditional methods for different types of tasks in simulacra. There is a lack of research in the specific application of AR that addresses occlusion introduced into these tasks. By conducting trials of simulated maintenance in an occluded area using AR technology, we found that the novice maintainer increased the accuracy of performance and decreased maintenance time when compared to traditional methods, while providing a subjectively easier method for instruction.

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X-RAY VISION: APPLICATION OF AUGMENTED REALITY IN AVIATION MAINTENANCE TO SIMPLIFY TASKS INHIBITED BY OCCLUSION

Justin R. Mcneely
Captain, United States Marine Corps
BS, Old Dominion University, 2014

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requirements for the degree of

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June 2022

Approved by: James J. Fan
Advisor

Perry L. McDowell
Co-Advisor

Gurminder Singh
Chair, Department of Computer Science

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This thesis examined the potential applications of augmented or mixed reality (AR/MR) technology and leveraging them in the context of the aviation maintenance community. Specifically, we examined whether using the 3D mapping and real-time space tracking technology of devices like the Microsoft HoloLens 2 can be used to make maintenance tasks easier in environments where the maintainer is not able to see into their workspace. With the complexities of aircraft construction, the prevalence of narrow, tight fitting spaces that are blocked by walls or obstructions is common. In the past, aviation maintainers have had to rely on memorizing 2D diagrams and feeling around dark, cramped spaces in order to determine where certain parts are located. Previous research in the field of AR primarily focuses on comparing AR methods to traditional methods for different types of tasks in simulacra. There is a lack of research in the specific application of AR that addresses occlusion introduced into these tasks. By conducting trials of simulated maintenance in an occluded area using AR technology, we found that the novice maintainer increased the accuracy of performance and decreased maintenance time when compared to traditional methods, while providing a subjectively easier method for instruction.

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LIST OF ACRONYMS AND ABBREVIATIONS

AR	augmented reality
ARC	augmented reality cued
CT	computed tomography
DOD	Department of Defense
DRMO	Defense Reutilization and Marketing Office
FPFH	Fast Point Feature Histogram
HMD	head-mounted display
HUD	heads-up display
IVAS	Integrated Visual Augmentation System
MIM	Maintenance Information Manuals
OOMA	Optimized-Organizational Maintenance Activity
PEMA	Portable Electronic Maintenance Aid
RAM	random-access memory
TC	traditionally cued
TNE	total number of errors
TPT	total procedure time VR virtual reality

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I. INTRODUCTION

A. RELEVANCE

For generations Navy and Marine Corps aviation have chased the elusive carrot on a stick, that being the single biggest metric by which they define their ability to fight: aircraft readiness. The largest current issue is that aviation readiness is far below type commander mission capable goals, meaning these units with all their military might do not have the aircraft available to conduct the required missions expected of them (Losey, 2020). This issue stems from a myriad of reasons. At the strategic level there are challenges with projecting life-cycle costs and appropriately funding multiple fiscal years of operation and maintenance costs (Rendon & Snider, 2019). However, at the tactical level this challenge is predominately due to a combination of a lack of parts availability combined with the lack of manpower and/or expertise to conduct maintenance. This thesis does not aim to address the parts availability problem, but instead focuses on how to improve the efficiency and interoperability of the maintainers across the fleet.

Maintenance processes across the Navy and Marine Corps are currently constrained to rigid, systematic procedures to ensure proper execution of the task as well as detailed documentation of every action conducted on the aircraft. This is paramount for the safety and security of our platforms and our service members. This means that for our maintainers to be agile and efficient at performing their objectives, they must obtain a high fidelity of skill and be given every advantage to make their job easier. Many maintenance practices take place in confined areas where the maintainer cannot directly see the object they need to manipulate. This reality, at best, means the task requires additional time to ensure the maintainer is manipulating the correct parts and does not make an error. At worst, this could lead to an error which could cause a Class A mishap. Due to the nature of aircraft design, these tight spaces where the maintainer cannot see are not going to go away. If the maintainer could see through the obstructing object to the pieces of equipment they need to manipulate, they could potentially reduce the time it takes to conduct the maintenance while also increasing their level of accuracy.

These improvements to accuracy and efficiency are already being discovered in the medical field. Computed tomography (CT)-guided intervention is a technique designed to access peculiar structures inside the body which is comparatively less risky than open surgery while still allowing the operator the necessary precision to minimize risk (Theilig et al., 2021). By using a CT scan of the phantom abdomen to model an augmented reality (AR) replica in virtual space, Park et al. were able to conduct the same procedure without the need for the patient and doctor to be next to a running CT machine during the entirety of the operation (Park et al., 2020). The advantage in this scenario is that this technique has been shown to be faster and more accurate than the traditional method. Additionally, by using this new technique, the operator and patient are not having to be exposed to radiation being emitted by the CT scanner used in traditional methods. This technology has also been explored in designing navigation systems for total knee arthroplasty and shows similar outcomes and benefits (Wang et al., 2019). The goal of this thesis is to provide evidence that these occlusion practices can be translated into the maintenance domain to provide maintainers with better spatial awareness and a more intuitive understanding of their environment.

B. BENEFIT OF STUDY

Currently, the limited number of studies specifically pertaining to AR in maintenance discuss observations in using AR as a method of providing instructions to the user. These findings suggest a positive correlation between novice maintainers and performance accuracy (Kennedy et al., 2020). Under the condition of the participant having little maintenance experience and little or no exposure to AR technology, Kennedy et al., found that the participant completed the task faster and with fewer mistakes. Observations in another study suggested that assembly tasks, like those seen in maintenance actions, lend themselves to being more precise and more efficient using AR than traditional methods of instruction (Angelopoulos, 2018). Other examinations reveal that overlaying virtual objects in virtual space atop real-world objects makes spatially orienting and understanding the instructions much easier than trying to translate 2D instructions to the referent object (Engelke et al., 2015). Referring back to the techniques found in the medical field, we can apply these examples in the maintenance field to overcome occluded environments and further build a robust use-case for AR systems in aviation maintenance. Should these experiments prove successful, such systems may evolve into the next generation of more intuitive and faster maintenance methods.

To bring these observations into context, the current maintenance field requires years of formal schooling before the maintainer is deemed qualified to conduct specific types of maintenance actions. With the current first-term contract of most enlisted service members being just four years, this means that they will spend more of their first enlistment learning the skills to perform their job than actually conducting the job. The above studies demonstrate that a person with little to no technical maintenance experience can execute a job at the same level of complexity as someone who has had years of technical training and experience with equal accuracy (Kennedy et al., 2020). The ramifications of this imply that by using intuitive AR programming to provide visual, auditory, and spatial cuing, maintenance practices can evolve to be easier to interpret, faster to complete, and more accurate all the while requiring less training by the user.

C. MOTIVATION

For many years the aviation community has stagnated in how it handles administrative processes and documentation. Traditional methods intentionally separate instruction from documentation and make file management an iterative process. This is slow and cumbersome, and it makes the overall maintenance process complex and difficult for the maintainer to master. Given the fact that AR utilizes digital technology which has the ability to integrate with other systems and adapt its software capabilities, it lends itself well to integrating these various processes into one seamless process, thereby increasing the warfighter’s capabilities. By starting at the root and maturing the instructional method for aviation maintenance using AR, we can then advance the timeline of introducing this technology into the fleet.

D. SCOPE

This thesis's purpose was to assess the accuracy and efficiency of using AR to conduct maintenance actions in areas which are occluded or partially occluded by other objects. It compared subjects' performance conducting maintenance while viewing a holographic projection of an obstructed object with their performance conducting the same maintenance procedure without a holographic projection. The findings of this research would further expand upon the potential AR devices, such as HoloLens 2, would have on streamlining, improving, and modernizing our Navy's aviation communities.

This study was not meant to be a singular proof that AR is the next evolution in aviation maintenance, but rather a part of a series of efforts to provide evidence that AR improves legacy practices. This study was not intended to capture all possible scenarios in which a maintainer might find an object occluded by another, nor is it specific to any type, model, or series of aircraft. Rather it examines simple generic maintenance processes commonly found across the Navy and Marine Corps, including ships and land vehicles. This study did not specifically evaluate any particular vendor's AR equipment.

This thesis attempted to answer the following questions:

Does the use of head-mounted AR enable the user to conduct the required operations faster than traditional means?

Does the use of head-mounted AR enable the user to conduct the required operations with fewer mistakes than traditional means?

Does the use of head-mounted AR feel subjectively more intuitive to the user than traditional means?

Does the use of head-mounted AR feel subjectively easier to the user than traditional means?

E. APPROACH

Our experiment measured the effects of AR on a user's ability to complete various types of maintenance tasks. The maintenance environment was set up to inhibit the user from being able to fully see with the naked eye the objects they are manipulating, which is similar to the conditions of flight line maintainers working in tight spaces behind aircraft maintenance panels. For the control portion, the subjects received instructions via physical documentation similar to the documentation found in a Portable Electronic Maintenance Aid (PEMA).

Prior to conducting the experiment, the subjects took an initial questionnaire to assess their experience in maintenance and using AR devices. Based on this experience, we blocked them into one of four sub-categories: Maintenance Novice-AR Novice, Maintenance Expert-AR Novice, Maintenance Novice-AR Expert, Maintenance Expert-AR Expert. Two procedural methods were assessed: with only the naked eye and with an AR headset providing virtual representations of occluded objects. Four maintenance tasks were examined: inspection of a hydraulic filter, repair of a pipe section, assembly of a cannon plug assembly, and installation of a missing panel. All four tasks were completed by the subjects using one of the two different procedural methods as guidance to complete the maintenance tasks. The task completion accuracy and speed were measured and compared across both test conditions. This data was blocked according to the subject's respective experience sub-category. This allowed us to determine which method performed the best for each maintenance tasks category. We designed the experiment this way in order to provide insight to support the concept of having an AR overlay of physical objects aids in the completion of the task as well as to gain insight into which categories of maintenance tasks are more suitable to AR-based assistance with occluded objects compared to legacy methods.

F. THESIS OUTLINE

The information presented in Chapter II begins by first defining the spectrum between virtual reality (VR), AR, and the real world. It will then provide a few examples of current experiments conducted using AR devices as well as provide some potential use-cases for leveraging this technology. It provides an overview of current military maintenance practices and how AR could potentially apply to these practices. Chapter III contains the method used in creating this thesis and clearly defines the problem which it addresses. Chapter III also defines the procedure and all material requirements used to conduct the experimental study. Chapter IV explains the results and analysis extracted from the experiment. Chapter V addresses the relevant information taken from Chapter IV within the context of this study’s purpose. Chapter V also draws conclusions based on the author’s interpretation of the information as well as provides additional recommendations for future work within this area of study.

II. BACKGROUND

A. MAINTENANCE PRACTICES IN NAVAL AVIATION

Both the commercial industry and the Department of Defense (DOD) expend an exorbitant number of resources on the maintenance of complex, high-valued platforms. In fact, in FY22, the Department of the Navy spent 34 percent of its $211.7 billion budget on operating and maintaining its platforms (Figure 1) (*Department of the Navy FY 2022 President*, n.d.). While purchasing of materiel for these expensive, exquisite platforms contributes significantly to the annual budget, a majority of the annual costs are accrued in the form of these operation and maintenance costs as well as labor costs (*Department of the Navy FY 2022 President*, n.d.). For decades the Navy and Marine Corps have worked through various initiatives, such as the Continuous Process Improvement Program, to try to optimize processes and increase efficiency to reduce these costs while ensuring high quality outputs required for safe operation of ships and aircraft. However, these efforts require very precise adherence to procedures to correctly conduct the required maintenance, which consumes a lot of time and money in delivering the designer's instructions to the maintainer.

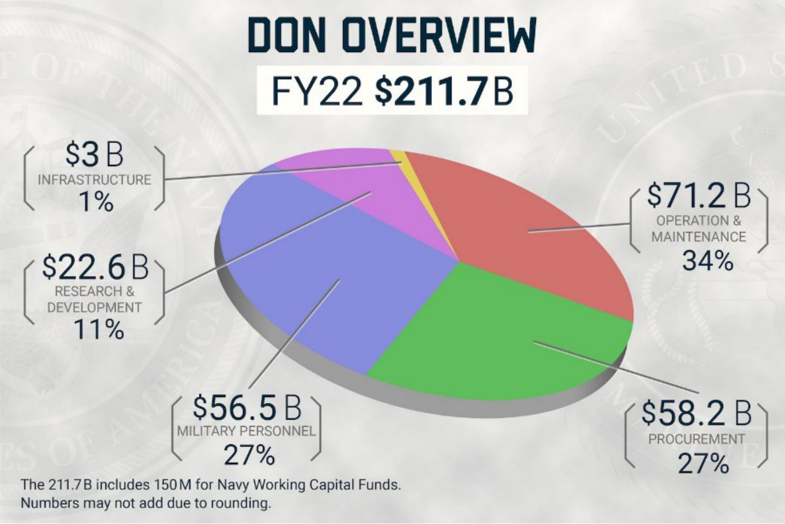


Figure 1. Department of the Navy Fiscal Year 2022 Budget Breakdown. Source: (*Department of the Navy FY 2022 President*, n.d.).

Before the age of computers, maintenance manuals were printed on paper in the form of a thorough, detailed book. This book outlined all of the possible maintenance actions that could be conducted for that specific platform or component and were within the scope of the maintainer's authorized abilities. Each maintenance task was cataloged and provided a step-by-step instruction for the entire task. An image of each component or subcomponent of the platform was also provided for each respective maintenance task, with each individual part on the component labeled. Many images also included an "exploded view" whereby the component was disassembled with its individual parts spaced around the component in the correct orientation and with a line connecting them to their respective attachment points.

As computers brought their immense power to many new areas, too often that merely resulted in an electronic version of the previous way of doing things, and maintenance instructions were no exception. The current standard in the aviation community is to use paper and 2D electronic rendering of instructions in the form of a technical manual to provide instructions. These instructions then have to be interpreted by the maintainer and translated into correctly conducting the complex task on the aircraft. Once the task is completed, it is then documented on either a separate paper or digital form. This method of isolating each individual process into their own entities is the way maintenance has been conducted for generations. Even in light of modern computer technology, the digital version of each of these tasks simply mirror the historical paper version. The DOD has yet to demonstrate a method in which the instruction, action, and documentation of the task be seamlessly woven together to increase the efficiency of the maintainer.

The Navy transitioned to using a digital 2D recreation of these manuals in the form of PDF files in the 1990s, known as maintenance information manuals (MIMs). The current iteration used by the Navy and Marine Corps is known as the PEMA and is composed of a ruggedized laptop which contains a compilation of MIMs specific to the squadron where it resides. The information displayed on these digital manuals are virtually identical to the paper manuals in every way. They provide an upgrade to the paper system by way of allowing the maintainer to search for specific words and carry a series of hundreds of manuals in a single laptop while also being compact and easily transportable.

Since aircraft are very complex and expensive objects, it is imperative that they be kept in top shape and everything that happens to them be documented. This is both a safety and a cost savings endeavor. Once a maintainer has completed a maintenance task, they then have a separate process to document the action. The Optimized-Organizational Maintenance Activity (OOMA) database is where the maintainer records and organizes all of their actions for each individual aircraft. In OOMA, the maintainer can track current maintenance requirements, open new maintenance requests, and complete existing requests. An additional advantage of this program is that it automatically matches each type of maintenance action to the proper technical directive and properly identifies if the aircraft is flight worthy. While this system makes it easy to quickly discern which aircraft are properly functioning and which need the most attention, the manner in which this information is recorded is by the individual maintainer manually filling out a digital form with approximately 66 lines of information. This form must be filled out for each individual maintenance action. It is easy to see that with each squadron containing dozens of aircraft, this can be a huge administrative burden on the unit.

Although this thesis does not focus on administrative record keeping and documentation, it is theoretically possible to replace these legacy methods of digital documentation with automated processes. By utilizing technologies such as Wi-Fi, Bluetooth, video/stereo recording, and traceable software, we have the ability to monitor a physical process as it is being completed rather than manually filing a report on it after the task has been completed. This not only streamlines the physical process, but also has the potential to provide more accurate and recallable data once the human's actions and biases have been taken out of the documentation process. I discuss this concept here because once the AR system of automated, intuitive instructional methods is mastered, the aforementioned burdensome processes can be intelligently woven into the AR system, thereby removing them from the maintainer's list of tasks.

B. AUGMENTED ENVIRONMENTS DEFINED

In order to fully appreciate the significance of AR and understand the specific context in which this article aims to achieve its goals, we must first specify what defines AR. One of the earlier examples provided by Milgram et al. establishes AR as existing along a spectrum between the completely physical world and the completely virtual world (Milgram et al., 1995). The physical world is the space which we currently occupy, the one which we perceive as being our true space. The virtual world is one which is completely generated by computers, which through enough emersion can give us the perception that we are in this artificial reality. AR, as depicted in Figure 2, bridges between these worlds, and incorporates behaviors given from one reality to interact with the other. One simplified example of this could be a projection of a virtual 3D object which appears to occupy physical space in real time.

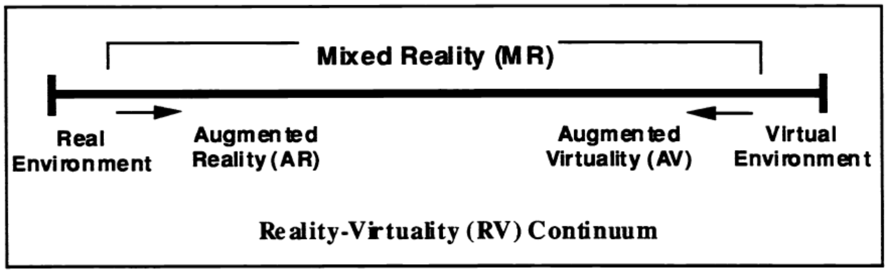


Figure 2. Reality-Virtuality Continuum. Source: Milgram et al. (1995).

The manner in which a person observes and interprets AR can be done through multiple display solutions (Figure 3). The two primary methods we will discuss are via a monitor-based display and a see-through display. A monitor-based display is a method of AR whereby the viewer looks at a computer screen that provides video of the physical world and overlays computer generated images upon the video to give the illusion that they are one in the same. This method of what Milgram et al. calls a “window-on-the-world” is deemed non-immersive and can be used for live or stored videos (Milgram et al., 1995). An example of this can commonly be seen today in phone applications which provide cartoon-like or realistically simulated filters which project over a person’s face, either through a still image or in real time. The advantage to these types of displays is that they can be generated using relatively common display solutions such as tablets, phones, and computer screens. Since these hand-held devices already have robust and mature software platforms, programming applications for them can be relatively easy to create. The disadvantage is that they require the user to hold the display up to the object of interest and use the camera integrated within the device. This limits the AR projections to within the capabilities of the camera as well as narrowing the field of view. Additionally, the requirement to hold up the device to the object or area of interest limits the utility of the application in activities where both hands are required.

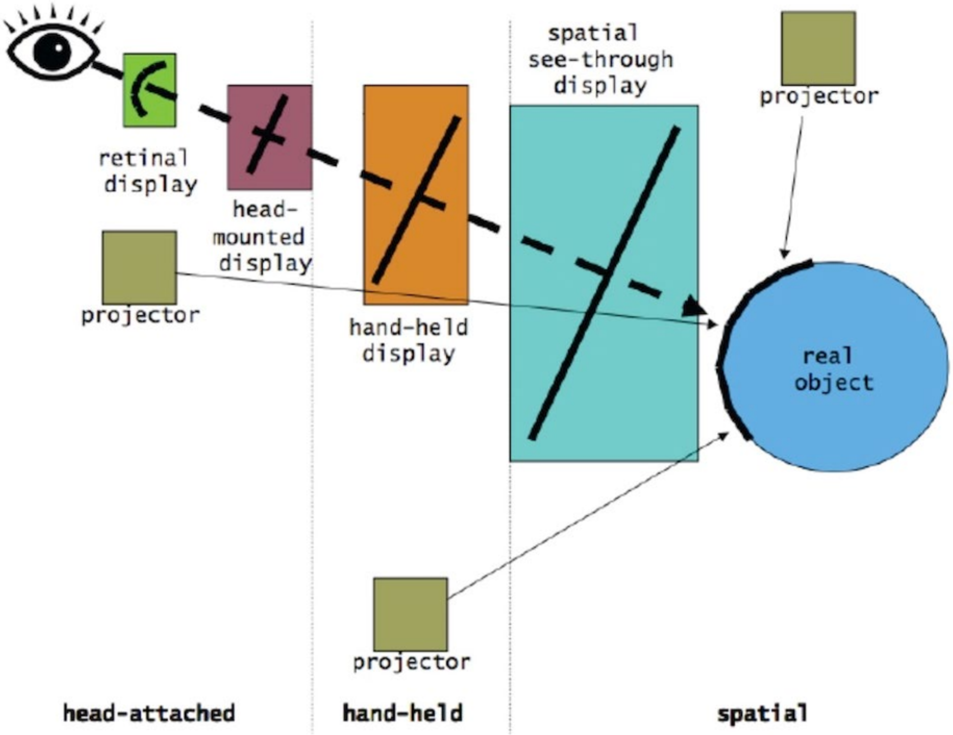


Figure 3. Examples of Image-Generation for AR Displays. Source: Bimber and Raskar (2006).

The other common display solution is the see-through display, also known as a head mounted display (HMD). This device works by resting on the user's head and projecting the virtual image onto a lens directly within the optical path between the user's eyes and the real world object (Bimber & Raskar, 2006). Since this display can overlay the entirety of the user's field of view, this display gives the illusion that the virtual object exists within the physical world and is considered more immersive. This method of display is what is used in devices such as the Microsoft HoloLens and HoloLens 2. The advantage to this display method is that it is hands-free, which allows the user to passively take in virtual information while conducting real-world tasks. What these devices also provide is a means to interact with the virtual object in a more natural manner using voice commands or hand gestures. The disadvantage is that the technology is currently much more complex and less accessible than hand-held displays.

C. LITERATURE REVIEW

1. AR for Maintenance Practices

AR offers the potential to design novel methods for conducting complex tasks in various applications. One of these specific fields is the maintenance industry (Ke et al., 2005). Due to maintenance tasks becoming more complex, it is imperative that during training the cognitive and fine motor skills which underline the procedural actions also be thoroughly incorporated into the training process (Webel et al., 2013). In a study conducted by Webel et al., they examined how to improve procedural maintenance tasks by way of providing AR specific training enhancements. Using AR technology provides the ability to leverage smartphone and tablet devices in ways previously not explored. Using the camera on these devices, the user can capture footage of a proper demonstration and, using smart software, create an "Adaptive Visual Aid" by inserting labels, notes, and visual ques into the recording (Webel et al., 2013). Another feature of AR is the ability for the software to project what the authors call "Direct and Indirect Visual Aids" (Webel et al., 2013). Essentially this is instructional imagery overlaid either right on top of (direct) or adjacent to (indirect) a live image being rendered through the camera (Figure 4). This imagery could provide contextual information as well as a means of integrated, intuitive instructions.

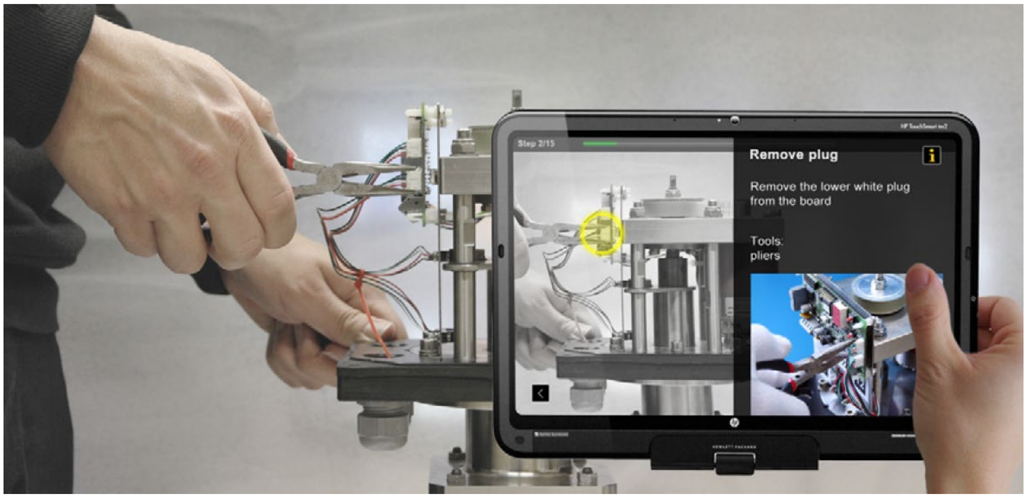


Figure 4. Demonstration of Using "Adaptive Visual Aids" for Assembly Task Training. Source: Webel et al. (2013).

This is beneficial because it allows the user to access the virtual information while simultaneously interacting with real-world object. This removes the need for external instruction manuals which require additional reading comprehension and translation. This also allows the user to learn tasks intuitively through exploration while developing their motor skills and learning new behaviors. Working on real objects and not virtual ones means they also receive live, tactile feedback in real time. Another technology explored in this research was integrating a haptic bracelet. This allowed for feedback that could be tailored to the task or used as a tactile notification system, such as the confirmation of proper object selection. Since these AR systems are digital, it is possible to record performance metrics of the user and accurately track progress for each individual. One risk the author identifies is that if the user solely learns a maintenance procedure through AR, then they may gain a dependency on the instructions. This can be mitigated by incorporating a period in the training where they must complete the task without the use of AR assistance. The authors conducted a skill transfer evaluation to examine the effectiveness of the aforementioned AR system. The control group used a traditional method to conduct the training procedure while the experimental group received instructions via AR. During the examination, both groups were allowed to reference photograph aids if they got stuck while conducting the procedure. The results showed that the AR group did not require the training aid and experienced almost no unsolved errors.

Meanwhile, the control group had on average 1.3 unsolved errors. The performance times of the AR group were also better than the control group. These results suggest that AR systems could be a promisingly useful technology for maintenance tasks and training (Webel et al., 2013).

The capabilities of AR offer the possibility to deliver the designer's instructions to the maintainer in a more intuitive form. The experiment conducted by Angelopoulos shows that AR can not only provide more intuitive instruction to the maintainer, but also make the maintenance task faster, more efficient, and more precise (Angelopoulos, 2018). The author tested this hypothesis by comparing traditionally cued (TC) maintenance procedures to AR cued (ARC) procedures against five maintenance tasks. By conducting a pairwise comparison, he examined the precision and efficiency of a set of subjects using technical publications against another set of subjects using a Microsoft HoloLens. His work built off other research like that of Tang et al. which demonstrates that AR can be more precise and, in some cases, faster than printed manual, LCD screen, or head-mounted display methods of instructions for assembling Duplo blocks (Tang et al., 2003). In Angelopoulos's experiment, the author objectively measured precision via observable human error. This was done by assigning tasks specifically to observe absolute error, cumulative error, referential absolute error, and complexity error in the maintainer. He measures efficiency by using a simple algorithm which compares the time spent conducting the task to the precision of the maintainer while also accounting for the relative complexity of the task. In Angelopoulos's study, the maintainers were treated to five tasks:

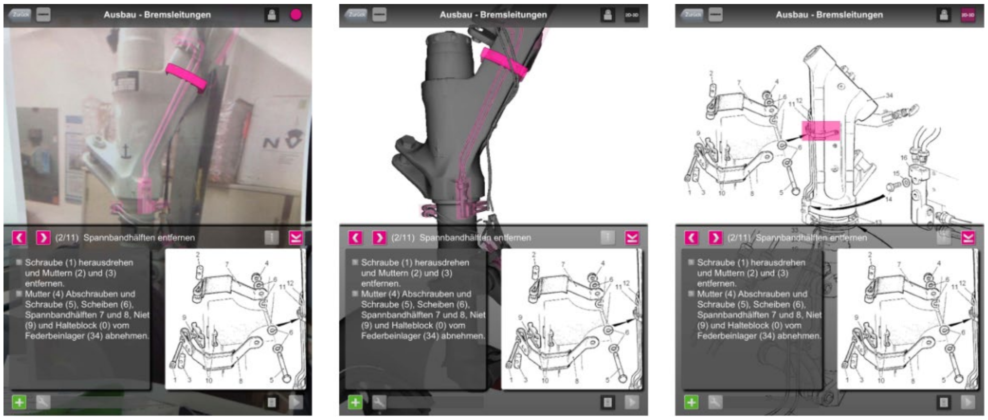
- Task 1 (absolute error) had the subject place 5 identical erector set parts a set distance from 5 L shapes on a paper within their workspace.
- Task 2 (cumulative error) had the subject place 5 identical erector set parts a distance from one L shape on a paper within their workspace.
- Task 3 (referential absolute error) had the subject place 5 identical erector set parts a distance from 5 L shapes on a paper within their workspace.
- Task 4 (complexity error) had the subject place 3 difference erector set parts in a pattern on a paper within their workspace.
- Task 5 (complexity error) had the subject assemble a larger object out of erector set parts and a wire. (Angelopoulos, 2018)

The subjects each participated in performing these tasks using both ARC and TC instructions. To build a case for industrial applicability, the author explained the difference between how AR communicates with the user when compared to traditional methods. The key distinction is that AR provides active information for the maintainer while traditional means are passive (Angelopoulos, 2018). This translated to AR having the ability to track performance, provide quality assurance, and review the maintainer's actions. These capabilities mean that AR are not just applicable to a training or near work environment, but also can be used to communicate during work and after work is completed. This active method has "the potential to reduce training requirements while improving quality of performance" (Angelopoulos, 2018). This inverse relationship is key to resolving the current performance shortfalls in flight line readiness. The author concludes that ARC is statistically more efficient than TC among all five tasks. The ARC method also is statistically more precise than TC on Tasks 3 and 5 while being not significantly different from TC for Tasks 1, 2, & 4. It is concluded that ARC is not more precise than TC in a general sense. Rather, that for assembly and small part placement tasks ARC is more efficient than TC but only equally as precise.

Research studies have shown using AR for maintenance tasks is suggested to be more efficient than traditional 2D methods. Engelke et al. attempted to address the reasoning behind this as well as further demonstrate AR's potential in the maintenance field. Historically in maintenance there has been a disconnect between the task at hand and the documentation. This required the user to have to "orient themselves inside the document and understand a task" all at once (Engelke et al., 2015). This increased cognitive load and added complexity to the procedure. Even with the advent of computer assisted instructions, these electronic documents were still complex in nature and required a baseline comprehension of the relevant task. Their research in AR instructional techniques aimed to reduce this inherit information transfer requirement and instead leverage the technology to focus the user on completing the task itself (Engelke et al., 2015). In their research, the authors have found that in a majority of instruction manuals had the following elements in common:

- A list of tasks that are described within the document
- Technical overview as a sketch, usually annotated with numbers and a legend with corresponding descriptions
- An abstract description of the task
- A detailed view that usually emphasizes or indicates a certain detail within the overview
- Hints, reminders, and attention signs (Danger, Warning, Caution) with descriptions
- Links to other media (e.g., video URL)
- Annotations or corrections of users that have performed the task

Engelke et al. (2015) demonstrated how to reproduce this information within an AR platform in a manner which is intuitive to the user and reduced the requirement of information transference. By using a phone or tablet device to project information on top of a real-world object, the authors were able to provide both a VR schematic with verbal instructions as well as contextual imagery overlaying the real object. They also incorporated a means to switch between the 3D VR schematic and camera view of the object, as seen in Figure 5.



(2/11) Spannbandhälften entfernen

- Schraube (1) herausdrehen und Muttern (2) und (3) entfernen.
- Mutter (4) Abschrauben und Schraube (5), Scheiben (6), Spannbandhälften 7 und 8, Niet (9) und Halteblock (0) vom Federbeinlager (34) abnehmen.

Figure 5. Example of a Maintenance Task on the Landing Gear of an Airplane Presented in Three Forms (from left to right): AR Mode, VR Mode, and a Traditional Sketch. Source: Engelke et al. (2015).

By doing this, the user could switch between different reference points to better understand the relationship between the physical object and the instructions. They acknowledge that this technique limited the user's ability to simultaneously work on the object while viewing these instructions, but their preliminary studies suggested that most users found this interface made the instructions and object they were working on more comprehensible. This may be because as this preliminary study traversed the boundaries between familiar legacy methods of instruction and into novel methods using AR in a manner which bridged the gap between old and new. They recommended having the user orient and observe the object using the AR interface and then setting the AR device aside to conduct the maintenance activity.

2. AR in Cases Dealing with Occlusion

As off-the-shelf AR products become more readily available, their potential applications in industry grow. Medical professionals in affiliation with the Oregon Health and Science University School of Medicine and the Perelman School of Medicine at the University of Pennsylvania conducted a case study to examine the effects of using AR technology in the practice of CT-guided lesion targeting in patients. Using a HoloLens 2 and a physical torso model, which they called a phantom, they conducted a case study to see if AR increased the efficiency of the operator and reduced the amount of radiation exposure that the patient received (Park et al., 2020). CT-guided intervention is a technique designed to access peculiar structures inside the body which is comparatively less risky than open surgery while still allowing the operator the necessary precision to minimize risk (Theilig et al., 2021). This technique is more desirable in that it requires less anesthesia and is less invasive that open surgery. One of the prevailing risks associated with this procedure is the patient and medical staff are exposed to radiation. Each time a CT scan is required, it increases radiation exposure. The less time the operator spends conducting the procedure and the fewer scans they require, the less exposure they and the patient receive. Therefore, the exploration of optimizing the technique is becoming more common following the introduction of Reality Augmentation for Medical Procedures in 2006 (Park et al., 2020). Park et al. were able to use AR by first conducting a preoperative CT scan of the phantom which could then be modeled in a virtual environment using a combination of

Meshmixer mesh decimation and Blender virtual rendering. This procedure took them less than an hour to complete. The team then used a custom application, created in the Unity game engine, to interface with the HoloLens 2 device. The HoloLens 2 projection was then applied to the real-world phantom using visual inspection. The operator was then able to follow a virtually projected 3D needle insertion guideline to see the optimal trajectory for the procedure (Figure 6).

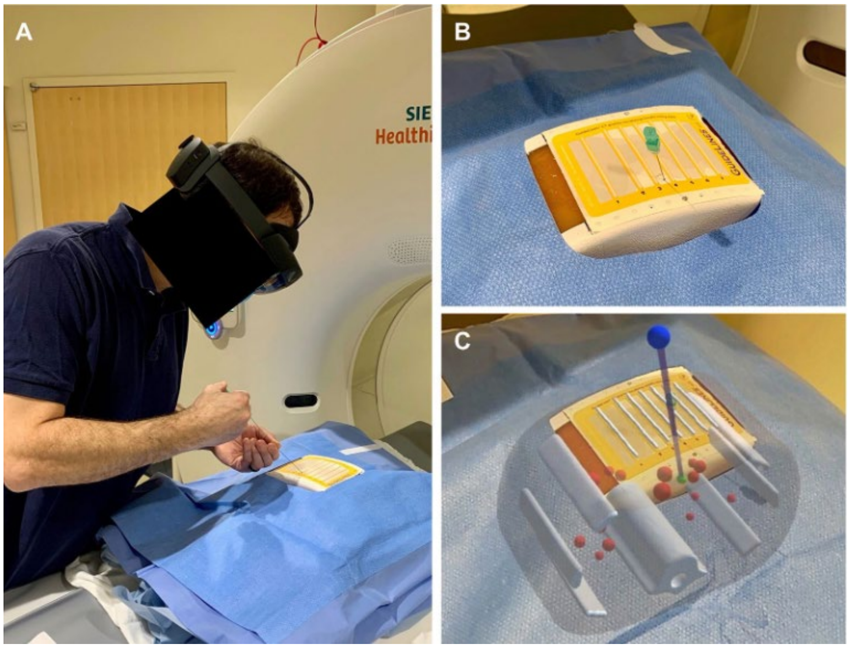


Figure 6. AR-Assisted Navigation Using HoloLens 2. (A) Participant performing the medical procedure while wearing a HoloLens 2. (B) Control image of needle insertion without AR. (C) View through HoloLens 2 of needle insertion with virtual needle guide and three-dimensional phantom model projected onto the true phantom. Source: Park et al. (2020).

A total of eight operators were used for this case study. Half of the operators conducted the procedure using the traditional CT-guided method while the other half used the HoloLens 2 method. Each operator was randomly assigned a condition, and all but one operator had zero experience with a HoloLens 2 device. Once they completed the first procedure with or without the HoloLens 2, they then conducted another procedure under the opposite experimental condition. The metrics recorded were the CT dose index, dose-length product, number of needle passes, and procedure time. The first needle pass distance to target using AR compared to not using AR was not statistically significant (p = 0.763). However, the results determined that AR was able to reduce the mean number of needles passed to reach the target lesion from 7.4 to 3.4 (p = 0.011). The use of AR was also able to reduce the procedure time from 8.93 minutes to 4.42 minutes (p = 0.027). These results suggest that using AR assistance in CT-guided targeting of lesions can increase the accuracy of the operator's needle passes and significantly reduce the time of the procedure, thus reducing the radiation exposure to the patient and operator.

Similar to the study conducted by Park et al., Wang et al., explored the applicability of HoloLens's AR technology in total knee arthroplasty (Wang et al., 2019). Their desire to explore this method was because it may be more effective than previous minimally invasive surgery techniques due to these traditional means having the propensity to cause trauma in the way of muscle vascular damage in the patient (Tzatzairis et al., 2018). This primarily stems from the operator typically having a very narrowly focused field of view at the site of the surgery and an inability to see the patient's anatomy outside of this narrow viewpoint. HoloLens is a desirable operational aid because if the operator can see an object that was previously being occluded in 3D space in real-time then it may reduce this risk of muscle vascular damage. This translates to better recovery while also avoiding X-ray radiation exposure from the alternative CT-guided procedures. Set up of this experiment began with first calibrating the HoloLens's position in 3D space. Using a binocular camera at a specified position and a specific sequence of markers placed on the HoloLens, the authors appropriately calibrated the HoloLens's real-world position to the holographic space similar to the depiction in Figure 7. They then aligned the HoloLens surface data with the artificial leg to ensure the projected AR imagery was aligned with the real-world objects. The femur and tibia analog were 3D printed using CT scan imagery from a patient and placed into the scene of the binocular camera. Their position is similarly calibrated, as well as a vision probe.

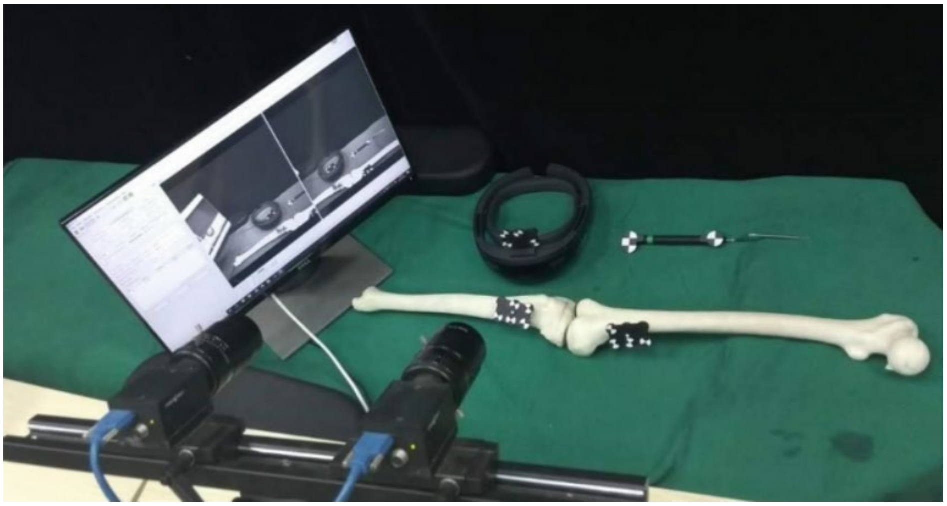


Figure 7. The Experimental Scene of Wang et al. Note the positional markers on the objects as well as the binocular camera used to calibrate their respective locations. Source: Wang et al. (2019).

After setting the scene, they then compared a geometry-based and descriptor-based algorithm to align the holographic projections using the same binocular camera. These methods were called super 4PCS and fast point feature histogram (FPFH), respectively. The overlaying process was compiled using a PC and the procedure was measured for accuracy and time. Using the root mean square error, measured in millimeters, it was concluded that the super 4PCS method (14.32mm) was more accurate than the FPFH-based method (19.07mm). As for time required, the super 4PCS method also performed better at 875.4 seconds compared to the FPFH-based method at 1311.5 seconds. Using the collected data from this calibration, the authors could get the holographic overlay to within 2.5mm of the real-world object. This finding is significant as this 2.5mm level of accuracy is within the clinical requirements for conducting surgery. One caveat of this system is that HoloLens uses a dynamic system to calibrate its environment called simultaneous localization and mapping (Wang et al., 2019). If the system were to refresh its environmental perception, then this could cause the imagery to drift from its original position over time. The author suggested overcoming this issue by rooting the holographic projection to an anchor object placed in the real world.

D. MILITARY APPLICATIONS

AR is still a novel technology and as such has currently only seen limited application within the DOD. Of these current uses, and probably the most known or discussed application, is in the use of an HMD for F-35 fighter pilots (Figure 8). This device uses technology made by Collins Aerospace, which is able to translate relevant, important information directly into the wearer's field of view. Traditionally, this information was displayed either on a computer monitor or see-through window fixed to the front of the cockpit. What the HMD in this helmet provides instead is not only the same level of information, but also real-time tracking of additional information, fixed to within the pilot's direct field of view, regardless of where they are looking. An reason for why this is so contextually important is say for example an external detector highlighted an enemy fighter, but it was outside the narrow window of the traditional see-through heads-up display (HUD). The pilot would have to rely on verbal callouts and search for the enemy aircraft by turning the plane before they are able to engage an enemy. With this HMD, they simply have to turn their head and search for the enemy to see its target indicator from any orientation. This can save seconds or even minutes for the pilot to engage the enemy while also enabling them to observe and fly independently to better set themselves up for the attack.

Figure 8. Point of View (Simulated) Using F-35 HMD Helmet. Source: Navy's F-35 Helmet Problem Fixed With TV Technology (n.d.).

Another AR technology, which is currently still in the testing phase, is the Army's Integrated Visual Augmentation System (IVAS). This is another type of HMD which mounts to the soldier's helmet and projects relevant HUD information, alternate camera views from external sources, night vision, and thermal vision among other uses ("The Army Is Finally Getting Its Futuristic Heads-up Display into More Soldiers' Hands This Year," 2022). The IVAS platform is based off the Microsoft HoloLens 2 and as such carries the same "remote user" screen sharing capability. This allows the wearers in an integrated team to share their points of view in real time to better make tactical decisions on the fly. Microsoft is also working with the Army to develop on-the-spot language translation and facial recognition programs to incorporate into the device. While it currently appears a very promising solution aimed to deliver many advantages to ground troops, it is still being developed and tested to ensure it can meet the rigors of field use and maintain reliability through a sustained operation.

A common practice used by service members across the DOD in the formation and planning of tactical, operational, and strategic exercises is called the "sandtable" exercise. In this exercise, the friendly forces build their strategy of how they intend to accomplish their mission and conduct a wargame to see how their plan performed against an opponent. The sandtable is usually a tabletop, field expedient terrain sketch, or even an actual sandbox with props which act as a representation of the combat area. The advantage AR could play into this practice is instead of low-fidelity physical mock-ups of the scenario being painstakingly built for each individual exercise, a program could be created in an HMD solution, like HoloLens 2, to recreate the scenario quickly and in high-fidelity. This device could use real-world satellite imagery taken to produce virtual 3D terrains and emplace detailed, relevant information inside of the terrain and animate it as necessary. The player models could be animated using a controller, hand gestures, or even voice commands. With AR's ability to create 3D models fixed into real space, the user would still be able to move around and interact with the virtual sandtable. Similar to current Zoom and Microsoft Teams video conferencing solutions, this exercise could be further enhanced by enabling remote sharing between users so others not present at the meeting can still observe. Additionally, if the key players of the scenario are separated from one another geographically, they can use a synchronized AR sandtable whereby they control their specific props, and the other players can see their actions in real time on their respective sandtable projections. This ability to virtually iterate through a better simulated exercise remotely from one another could be a powerful tool in enhancing operational planning exercises in the future.

E. CONSIDERATIONS FOR USING AR IN MILITARY MAINTENANCE TASKS

We have shown examples where AR has benefited a maintainer’s ability to complete complex tasks. The ability for AR to introduce training aids and other methods of guidance reduced the cognitive load on the maintainer (Webel et al., 2013). This capability is unique to AR and doesn't apply to other training methods such as VR or 2D simulations, as they do not fully replicate the scenario in the same level of fidelity as actually putting hands on the real-world object and manipulating it. Minute changes in each iteration of a maintenance task can significantly affect the overall training effect. The lack of or overpronounced implementation of these effects in a virtual environment could lead to negative training or a knowledge gap. Evolving beyond training, in the everyday application of performing complex tasks it is important that the method of instruction be easy enough to interpret to prevent mental fatigue and reduce the probability of human error. By using the techniques of Angelopoulos and Engelke et al. discussed earlier, the DOD could leverage the abilities of AR devices such as HoloLens 2 to simultaneously provide MIMs instructions, visual and auditory cueing, remote expert assistance when necessary, and live performance tracking and data documentation.

The ability to combine what have traditionally been independent processes into one intuitive task would be a force multiplier if it could be implemented across the fleet. With this concept being in its infancy, the key considerations to correctly implement this idea is to first prove that AR can be as precise and more efficient as legacy methods, which it has done. It must also be intuitive enough to aid the maintainer while reducing cognitive load, which has also been shown. For broader adoption by the DOD, it must also be scalable, cost-effective, interoperable with legacy systems and platforms, and deliverable in a timely manner. One gap that has not been demonstrated by these other studies is the efficiency of

AR when the objects are in confined areas and are obscured. This thesis examined if there is a difference in performance between traditional methods and the use of AR in an occluded space.

III. METHOD

A. PARTICIPANTS

For data collection, the population of interest of this study was any DOD civilian or military personnel. No restrictions were imposed regarding time in service, level of maintenance experience, gender, or any other demographic. The only physical limitation was that they must have normal color vision with or without corrective lenses and not have any history of photosensitive epilepsy or be prone to motion sickness. The sample size requested was between 16 and 40 participants and we had 25 participants who volunteered from the Naval Postgraduate School based in Monterey, California. Of these participants, 18 of them stated they had prior maintenance experience with either formal training or as a form of hobby during their lives. Seven of the participants stated they have no prior maintenance experience. A total of 14 participants played video games, with almost all of them stating they played less than four hours a week. While a total of 17 participants stated they had used a VR device, such as the Oculus Quest 2, only 11 claimed to have used an AR HMD similar to the one used in this study.

B. DESIGN OVERVIEW

This pilot study was completed in a single-phase using a between-subjects design method. Due to the uniqueness of the tasks and relatively low number of subjects, this method was chosen over a within-subjects analysis. Each participant was placed into one of two groups: the AR test group or the control group. Subjects were randomly assigned to the AR group or the control group before completing the pre-test questionnaire. Every participant, regardless of which group they were assigned, conducted all four maintenance tasks.

Each maintenance task was selected specifically because it replicated a real-world maintenance action conducted in the Department of the Navy and each were different enough from one another as to provide a relatively significant level of variance between tasks. We used data from the pre-test questionnaire to block participants for data analysis according to familiarity with maintenance tasks and AR devices. We also recorded other factors, such as the frequency in which they played videos games and what types of games they played, using the pre-test questionnaire.

While completing the tasks, we timed each participant on how long it took them to complete each task. After completing all four tasks, we gave the participant a post-test to gauge their subjective measurement of difficulty in completing the tasks and using the AR device. We also directly observed the subjects in a non-intrusive manner to record when they made a mistake in the procedures. After all four tasks were completed and the participant had left, each task was further inspected in detail to discover any errors the experiment missed before resetting the experiment for the next participant.

C. MATERIALS

1. Physical Setup

The physical mockup of the aircraft interior space (Figure 9) was built using a combination of common household items found at a typical hardware store and old, scrapped subcomponents acquired through the Defense Reutilization and Marketing Office (DRMO). We specifically chose the DRMO components to enable examination of four distinct tasks: a cross-bolting task, a simple installation task, a complex installation task, and an inspection task. Each of these tasks simulate real-world scenarios given to Sailors and Marines in the fleet.

Subjects completed the cross-bolting task using a panel with six Phillips head screws which had to be installed in a specific sequence. They completed the simple installation task by correctly sliding a pipe sleeve onto a gap between two pipes and tightening its hose clamps. For the complex installation task, subjects had to follow a schematic of a cannon plug assembly in order to install the correct color-coded wires to the correct ports. The inspection task was unique in that it required the participant to first remove the hydraulic filter from its connectors, inspect the inserts, clean them, if necessary, then reinstall the filter in the correct orientation. Each of these tasks were to be examined individually to see which tasks were aided or inhibited by the use of AR technology. The box was structured to include two 2.5-inch-wide pipes at the point of entry to create a physical and visual obstruction during execution. The point of entry was designed to be wide enough for two-handed manipulation, but not so wide as to allow the participant to put their head inside of the box.

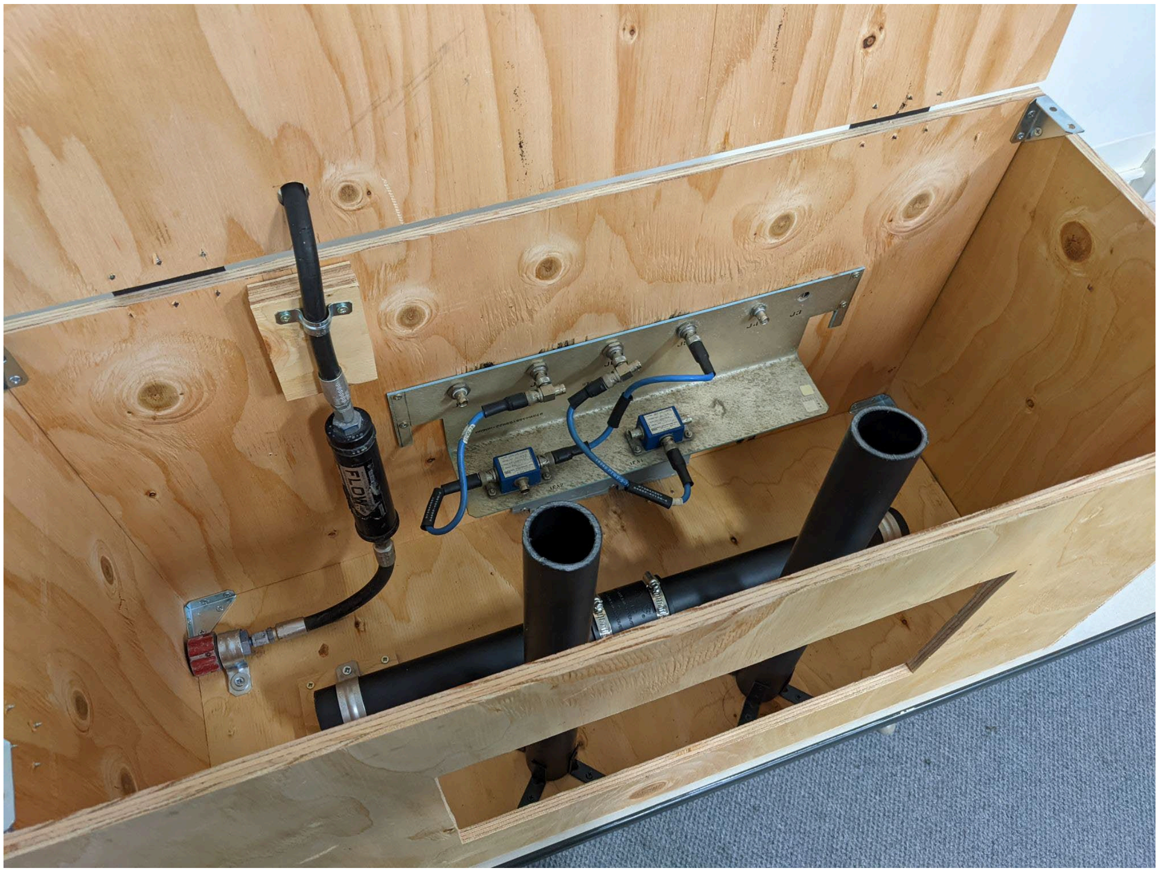


Figure 9. Top-Down Perspective of Assembled Mockup Chamber with Lid Open.

2. Software

All AR models, animations, and logic were created by Naval Postgraduate School staff using the Unity game engine, Blender for textures, and C-Sharp scripting language for back-end logic. The AR guidance system was completed using the parallel authoring technique developed by a faculty member here at NPS. The 2D instructions and animations were made using the same technologies. The 2D instructional method is able to run on any modern personal computer.

3. Hardware

The AR headset used was a HoloLens 2 operating on the Windows 10 Holographic operating system. This AR headset has a resolution of 1440 x 936 (2K). The horizontal field of view is 52 degrees. It contains four visible light cameras and two infrared cameras for head and eye tracking, respectively. It can take 8MP still photos and 1080p30 videos of the user's point of view. It is capable of real-time eye tracking, hand-tracking, and voice command. It has an on-board memory of 64GB and 4GB of random-access memory (RAM). It is Wi-Fi 5 and Bluetooth enabled. The PC used during the study was a HP Envy 13.3" 4K Ultra HD Touch-Screen Laptop. It contains a 10th Gen Intel i7-1065G7 processor and a 3.9 GHz processing speed. It possesses 8GB of RAM, 512GB solid state drive, is Wi-Fi 6 enabled, and uses Bluetooth 5.0.

D. PROCEDURE

1. Setup of Study

The initial state of the mockup was to have the lid closed and access port oriented towards the participant. For task 1, the panel was removed from the circuit box and placed in the staging area along with its respective screws. On task 2, the pipe sleeve was initially attached to the right pipe segment and the clamps were removed and placed in the staging area to the right of the mockup. The cannon plug array for task 3 was free of any wires and only the wires required for the experiment were placed in the staging area. The hydraulic system of task 4 was assembled with the filter properly installed with the arrow oriented towards the downward direction. The experimenter ensured all the parts that the subject had to reinstall to complete the maintenance procedures were removed from the box before beginning each test. All disconnected components in the staging area were laid out from left to right in accordance with their task. For both the control and test group, the participants were given a box wrench, a Phillips-head screwdriver, a flat-head screwdriver, a torque wrench with a Phillips-head bit, and toothpicks as tools for conducting the study. These tools were all laid beside the mockup, along with the disconnected parts to be installed during the experiment (Figure 10).

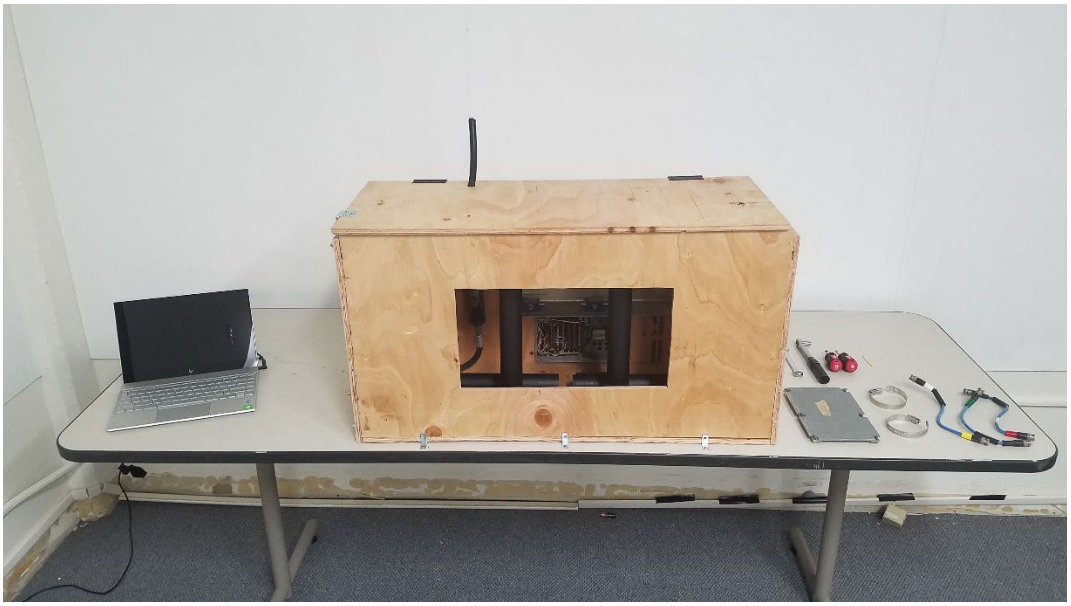
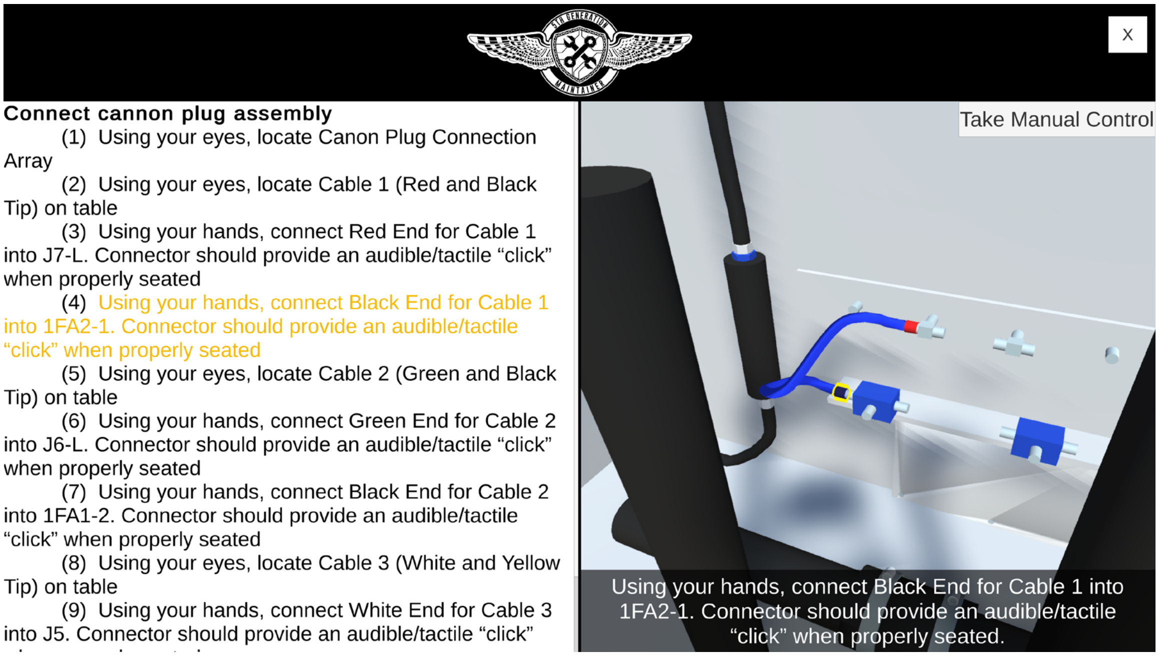


Figure 10. Initial State of Mockup

The computer used for the experiment was laid on the left side of the mockup. It was used to record the participants' pre and post-test questionnaires as well as provide the 2D instructions and animations (Figure 11). This 2D instructional method was used in both the control and test groups. For the control group, it provided written, audio, and 2D animation instructions for each step of all four tasks. For the test group, if only provided written instructions and 2D animations. The test group received audio instructions through the HoloLens 2 headset as well as 3D animations projected onto the physical mockup (Figure 12). In both test cases, the computer was connected to a 50-inch TV situated to the left of the table to project a larger, easier to read viewing of the 2D instructions, animations, and figures for the subjects.



Connect cannon plug assembly

(1) Using your eyes, locate Canon Plug Connection Array

(2) Using your eyes, locate Cable 1 (Red and Black Tip) on table

(3) Using your hands, connect Red End for Cable 1 into J7-L. Connector should provide an audible/tactile "click" when properly seated

(4) Using your hands, connect Black End for Cable 1 into 1FA2-1. Connector should provide an audible/tactile "click" when properly seated

(5) Using your eyes, locate Cable 2 (Green and Black Tip) on table

(6) Using your hands, connect Green End for Cable 2 into J6-L. Connector should provide an audible/tactile "click" when properly seated

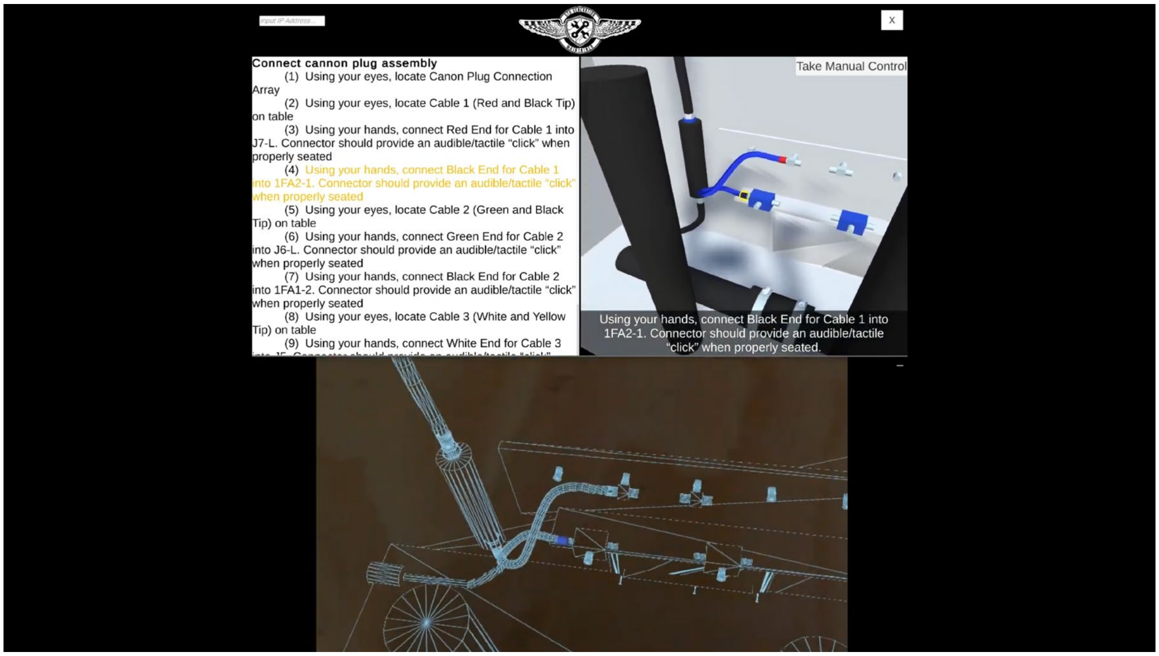
(7) Using your hands, connect Black End for Cable 2 into 1FA1-2. Connector should provide an audible/tactile "click" when properly seated

(8) Using your eyes, locate Cable 3 (White and Yellow Tip) on table

(9) Using your hands, connect White End for Cable 3 into J5. Connector should provide an audible/tactile "click"

Using your hands, connect Black End for Cable 1 into 1FA2-1. Connector should provide an audible/tactile "click" when properly seated.

Figure 11. Screenshot of 2D Instructions (left) and Animation (right)



Connect cannon plug assembly

(1) Using your eyes, locate Canon Plug Connection Array

(2) Using your eyes, locate Cable 1 (Red and Black Tip) on table

(3) Using your hands, connect Red End for Cable 1 into J7-L. Connector should provide an audible/tactile "click" when properly seated

(4) Using your hands, connect Black End for Cable 1 into 1FA2-1. Connector should provide an audible/tactile "click" when properly seated

(5) Using your eyes, locate Cable 2 (Green and Black Tip) on table

(6) Using your hands, connect Green End for Cable 2 into J6-L. Connector should provide an audible/tactile "click" when properly seated

(7) Using your hands, connect Black End for Cable 2 into 1FA1-2. Connector should provide an audible/tactile "click" when properly seated

(8) Using your eyes, locate Cable 3 (White and Yellow Tip) on table

(9) Using your hands, connect White End for Cable 3

Using your hands, connect Black End for Cable 1 into 1FA2-1. Connector should provide an audible/tactile "click" when properly seated.

Figure 12. Screenshot of 2D Instructions (above) and HoloLens 2 3D Projection (below) Note: 2D image of HoloLens 2 projection does not fully depict the level of detail and spatial perspective as perceived when wearing the headset in person.

2. Initial Briefing

Upon the arrival of the participant, they were informed of the nature and voluntary status of the experiment. Once the participant had been briefed, the experimenter gave them a consent form and pre-test questionnaire to complete and informed them to raise any questions they had at any point in time during the experiment. They were also notified that all information collected from this experiment would be anonymous and solely used for data collection purposes. We then randomly assigned them to either the AR test group or control group; we did not inform them of which group we had assigned them to avoid imparting biases on the procedure. Once they had been assigned to their group, they then completed their consent form and pre-test questionnaire.

3. Orientation and Training of Maintenance Tasks

We gave the participants a brief orientation on the physical mockup and explained to them how each of the tools worked. If they were unfamiliar with a tool, the investigator demonstrated for them how to use the tools in a similar manner to how they would be conducting the actual task. If they were selected for the AR component of the study, they were given an orientation on how to use the HoloLens 2 device and given a few minutes to familiarize themselves with it. In both the control group and test group, the participant was instructed that they could only look inside the box or manipulate objects within the box; they were not permitted to conduct both actions simultaneously. Despite the port opening being large enough to both see and work within, we deliberately chose this artificially induced challenge to simulate a scenario in which a maintainer would not have the ability to see the object they are working on. This situation also allowed the investigator the ability to observe the participant's hands during the experiment.

4. Conducting the Study

The objective measure of the study was to examine the speed and accuracy of the participants. To calculate this, each participant was timed during each individual step for each task. They were also observed during the experiment to see if they conducted a step improperly or in improper sequence. After each participant was finished, the observer inspected all the tasks to check for errors in the final build of the mockup. The observer recorded all times, errors, and any comments on a paper spreadsheet while the participant was conducting the study. This raw data was later added to the aggregated Excel spreadsheet to track all participant information.

Task 1 consisted of 14 steps. The participant was required to install a missing panel onto a circuit box, tighten the screws in a specific sequence, then use a torque wrench to ensure they were tightened to the proper level of torque. This asymmetrical panel contained six captive screws which the participant needed to tighten in a star pattern, to simulate a mechanical object that requires even force to be applied across its face. Once the six screws were installed, the torque wrench was then to be inspected to ensure it was set to fifteen inch-pounds. Upon ensuring proper torque on the wrench, the participant then used it to snug each screw to the specified tightness, doing so in the same star pattern as when they initially installed the screws.

Task 2 consisted of 7 steps. Once the participant identified the proper pipe, they then slid the pipe sleeve across the gap between the left and right horizontal pipes. They were then instructed to attach and begin hand tightening the left retaining band over the sleeve, then the right. Once both were loosely in position, they were then instructed to take a flathead screwdriver, and tighten the two retaining bands until snug. They were informed the band need only be slightly tight, as overtightening could cause damage. Upon tightening both bands, the participant was instructed to physically check to ensure the sleeve was properly attached and the bands were snug.

Task 3 consisted of 10 steps. The first step was to locate the cannon plug array. Once the participant completed this, they would then systematically attach and route three different cables. Each cable had a cannon plug connector on each end and the ends were marked with colored tape to distinguish one from another. For each cable, the participant needed to place one end into a top plug, oriented toward the individual, and then attach the other end to a small box containing three separate connection points. Among the things the investigator verified were the location and orientation of the cables once installed, whether the correct color was in its respective port, and whether the connectors were properly seated.

Task 4 consisted of 11 steps. The hydraulic filter was assembled along the back left corner of the enclosure. The participant was instructed to remove it in a specific order using a box wrench, then inspect the inside of the thread points to see if there is any debris creating an obstruction. They were supplied with a toothpick to remove any surface obstruction if they noticed any, even though the filter was technically clean. Once they determined the filter was free of any obstructions, the were to then reinstall the hydraulic filter in the reverse sequence of when the removed it. They were also instructed to ensure the flow arrow was oriented in the downward direction.

5. Following the Study

Upon the completion of the final task, the participant was given a post-test questionnaire. This questionnaire was to collect their subjective perception of the level of difficulty for each task. They were instructed to leave a mark on a line ranging from "Very Difficult" to "Very Easy" for the task itself. This mark was later measured and given a relative score ranging from zero to one hundred, with one hundred being considered the hardest difficulty and zero being considered the easiest. If they were in the test group, the participant was also asked to rate relevant factors to the HMD such as the comfort of the headset, intuitiveness of the display, and complexity of the headset as well as how impactful the use of the AR device was on their ability to conduct each task. They were instructed to mark a line ranging from "Significantly More Difficult" to "Significantly Easier," with the middle of the line being considered AR as having no effect. The scoring system for this data was between -100, meaning the AR made the task significantly more difficult, to 100, meaning the AR made the task significantly easier. Once they had completed and turned in their post-test questionnaire, they were reminded of the anonymity of the data collection and thanked for their participation. Once they were finished and all data had been recorded, the observer then reset the physical mockup, 2D instructions, HoloLens, and questionnaires for the next participant.

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IV. RESULTS AND LIMITATIONS

A. ANALYSIS

A 1-factor ANOVA test was conducted to determine the effects of the test condition on the time required to complete all four tasks and the number of errors observed. Blocking category showed no statistical significance in total procedure time (TPT) with a p-value of 0.26. The blocking categories also showed no significance in total number of errors (TNE) with a p-value of 0.15. The blocking categories were, therefore, not examined in further analysis with the exception of comparing those with prior maintenance experience versus no prior maintenance experience. In addition to the total procedure, each individual task was also analyzed for time to complete the task and number of errors committed.

1. Head-Mounted AR and Time to Complete Tasks

To determine if AR had in a role in making the participant faster, speed in this context was defined as the rate at which a process occurred from beginning to end. The speed of each participant was measured based on the length of time they required to complete each task. This time was recorded and examined for each task. The total time required for them to complete all four tasks is considered to be the TPT.

a. Task 1 (Install Panel and Torque Screws)

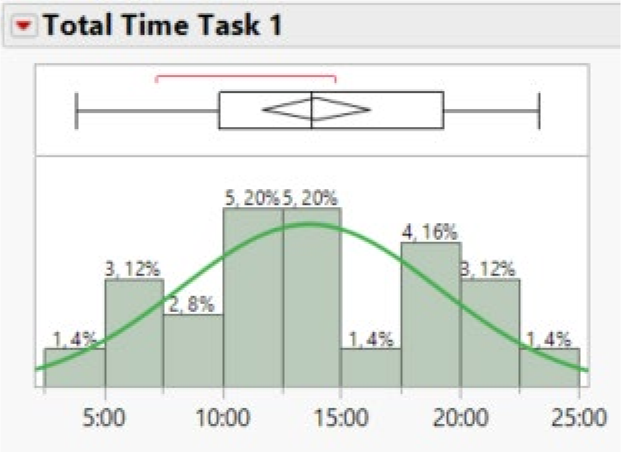


Figure 13. Distribution of Time to Complete Task 1 (M=837.8sec, SD=332.85sec, SEM=66.57sec, CI_{95}[700.40, 975.19sec], N=25)

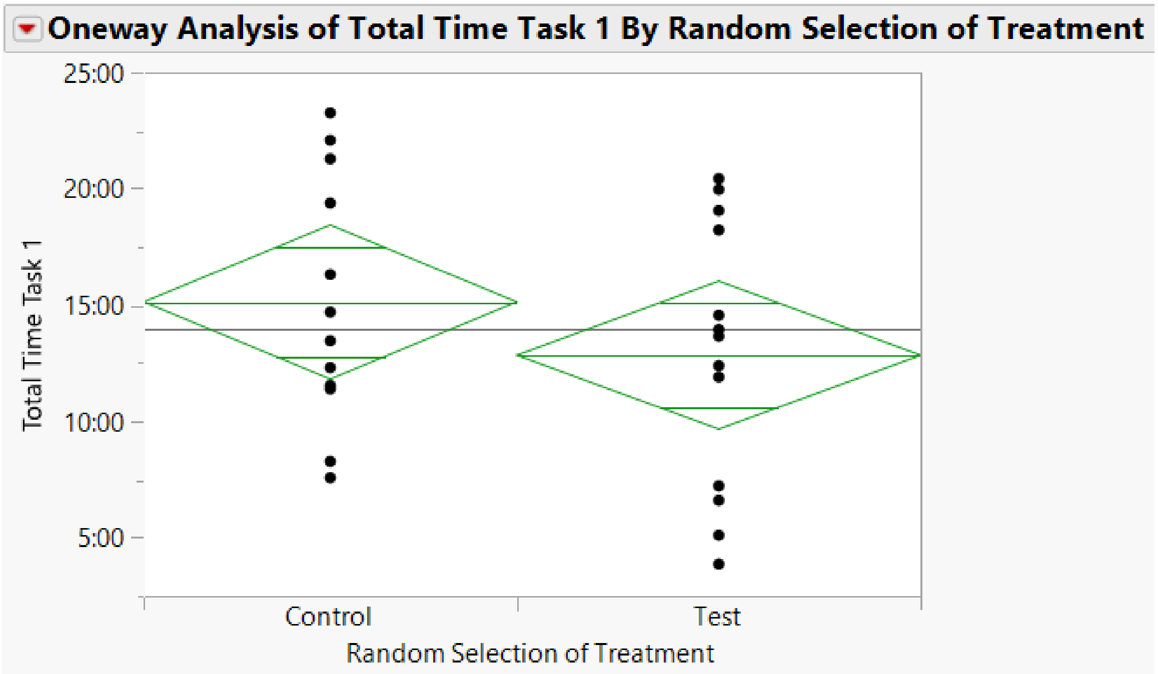


Figure 14. 1-Factor ANOVA of Time to Complete Task 1. Results are not statistically significant but indicate the use of AR has a shorter mean time to complete task. (R-square=0.04, DF=24, p-value=0.31)

b. Task 2 (Install Pipe Sleeve)

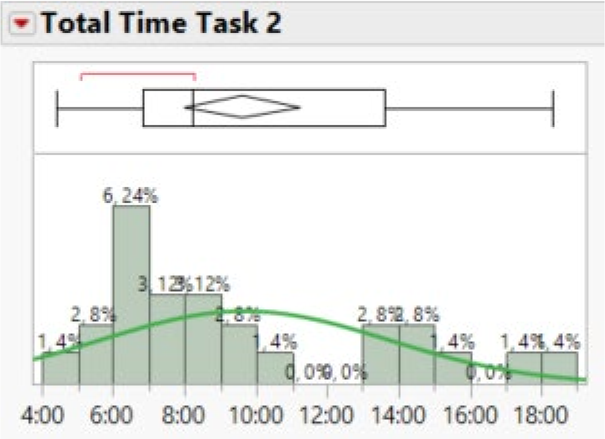


Figure 15. Distribution of Time to Complete Task 2 (M=577.44sec, SD=237.43sec, SEM=47.49sec, CI_{95}[479.43, 675.45sec], N=25)

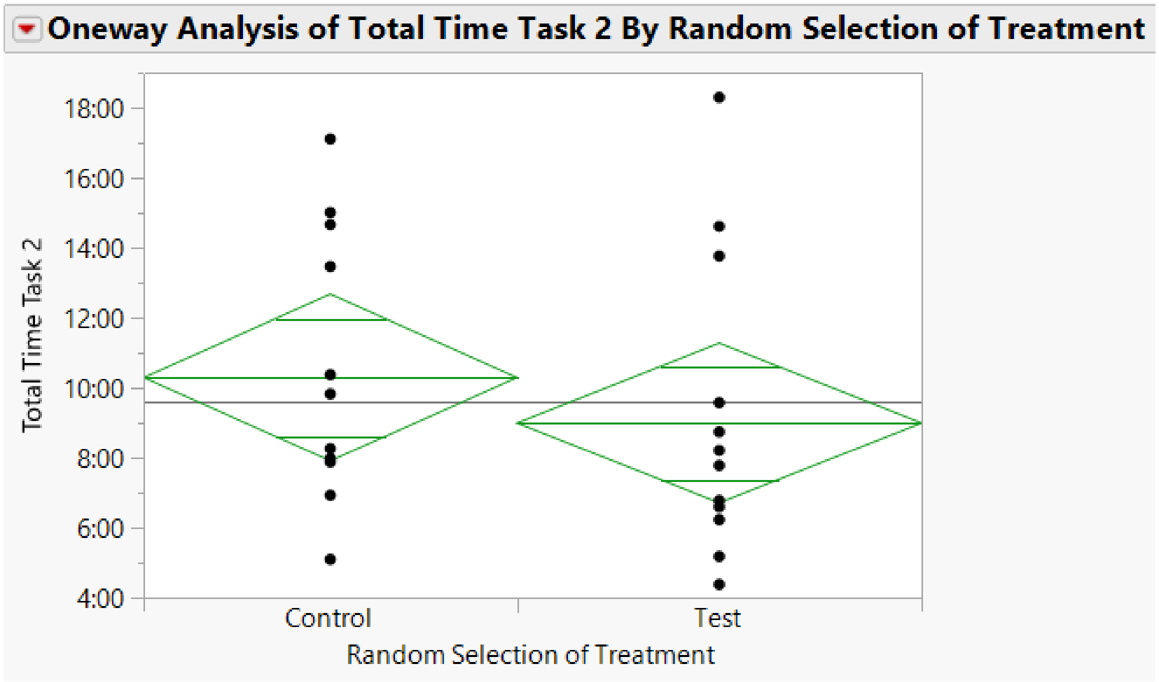


Figure 16. 1-Factor ANOVA of Time to Complete Task 2. Results are not statistically significant but indicate the use of AR has a shorter mean time to complete task. (R-square=0.03, DF=24, p-value=0.42)

c. Task 3 (Assemble Cannon Plug Assembly)

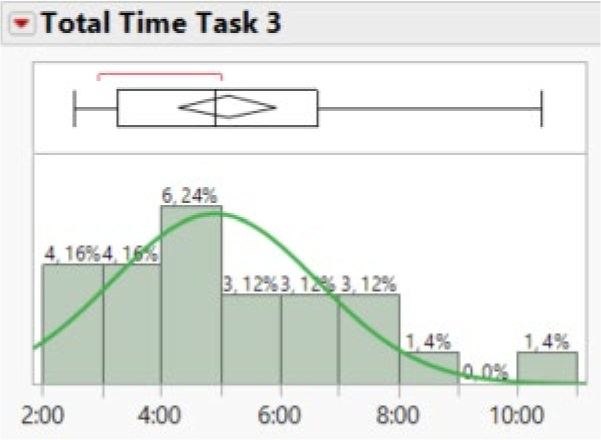


Figure 17. Distribution of Time to Complete Task 3 (M=307.44sec, SD=121.08sec, SEM=24.22sec, CI95[257.46, 357.42sec], N=25)

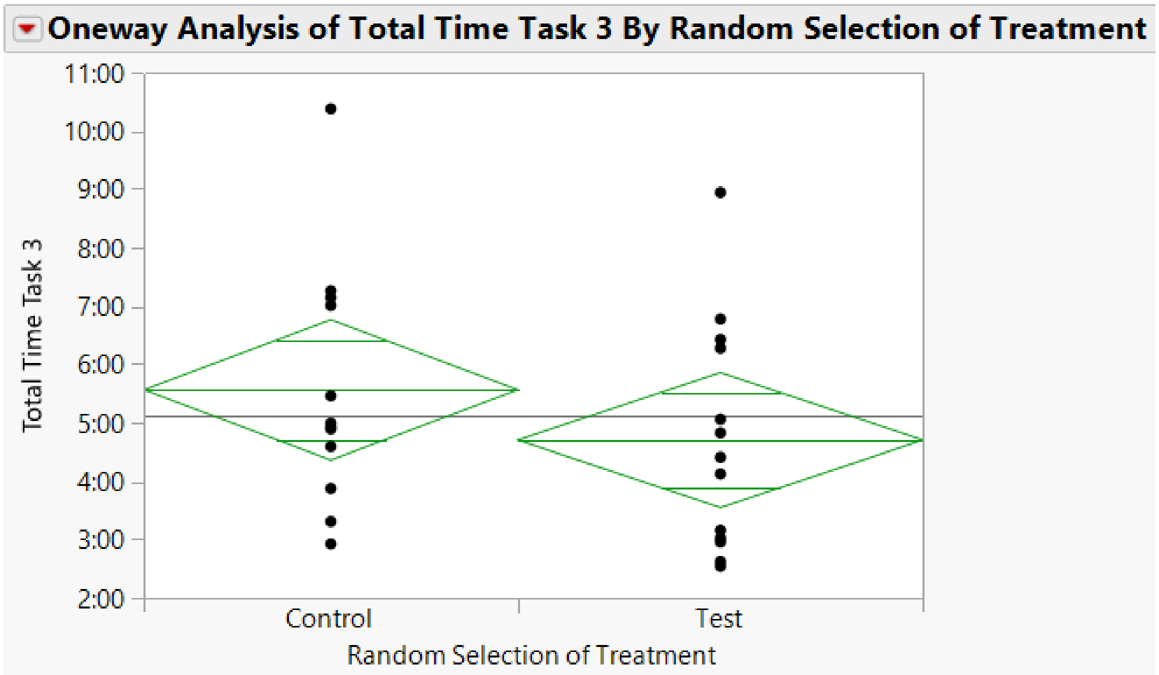


Figure 18. 1-Factor ANOVA of Time to Complete Task 3. Results are not statistically significant but indicate the use of AR has a shorter mean time to complete task. (R-square=0.05, DF=24, p-value=0.3)

d. Task 4 (Inspect Hydraulic Filter)

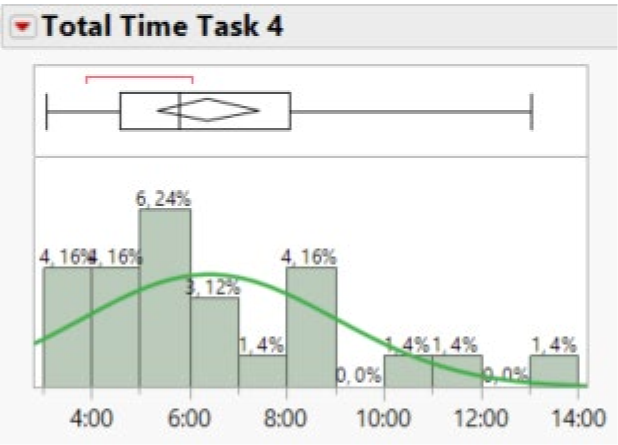


Figure 19. Distribution of Time to Complete Task 4 (M=383.88sec, SD=153.29sec, SEM=30.66sec, CI_{95}[320.60, 447.15sec], N=25)

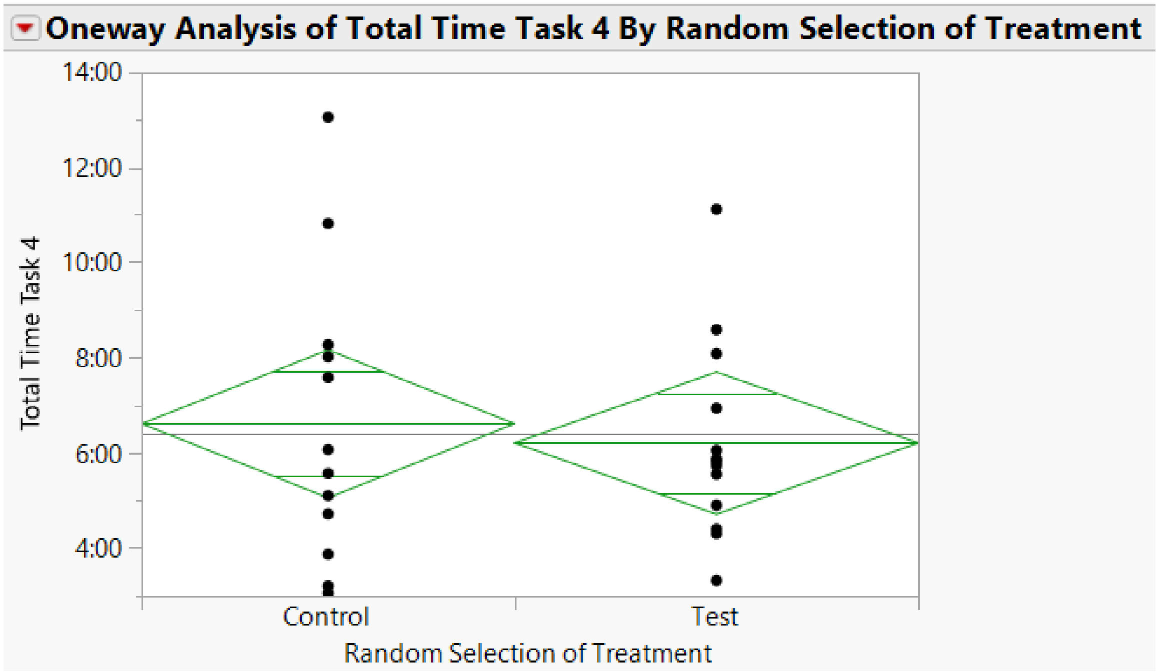


Figure 20. 1-Factor ANOVA of Time to Complete Task 4. Results are not statistically significant and do not indicate the use of AR as having an impact on time to complete task 4. (R-square<0.01, DF=24, p-value=0.7)

e. Total Procedure Time

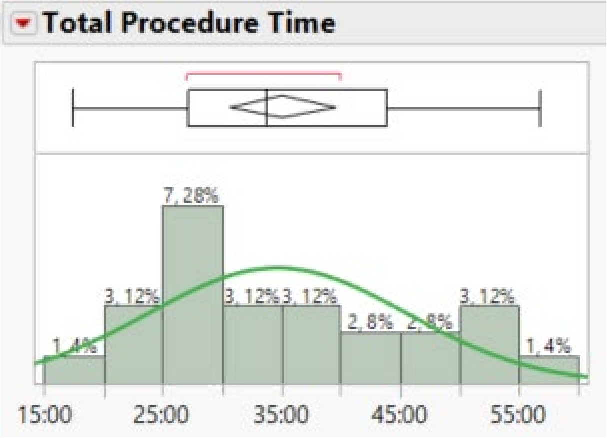


Figure 21. Distribution of Time to Complete Total Procedure (M=2106.56sec, SD=655.24sec, SEM=131.05sec, CI_{95}[1836.09, 2377.03sec], N=25)

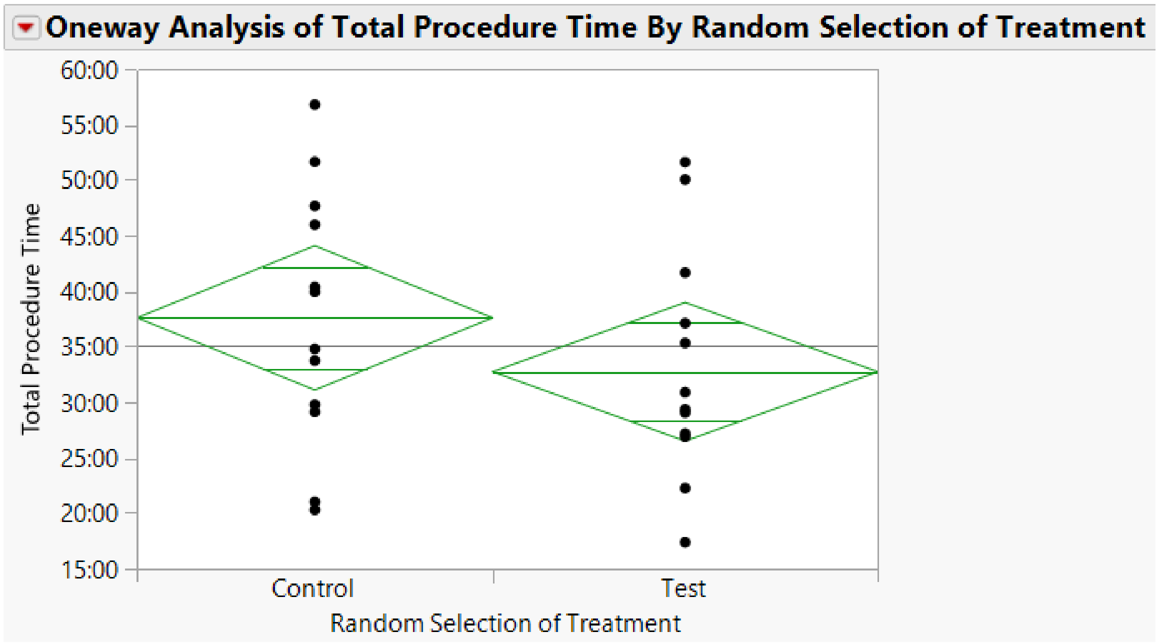


Figure 22. 1-Factor ANOVA of Time to Complete Total Procedure. Results are not statistically significant but indicate the use of AR has a shorter mean time to complete task. (R-square=0.05, DF=24, p-value=0.29)

2. Head-Mounted AR and Accuracy of Task Completion

The second quantitative factor examined was accuracy. In the context of this study, this was equal to the total number of errors the participant committed during each task and during the entire procedure. Each error was recorded whenever the participant failed to complete a step correctly. Due to the variance between tasks, this amounted to some tasks having multiple errors recorded and others having very few. Since some of these tasks exhibited few errors, not much statistical relevance could be drawn from their results.

a. Task 1 (Install Panel and Torque Screws)

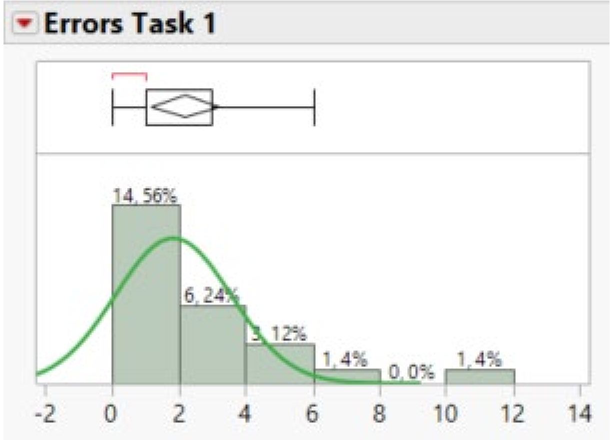


Figure 23. Total Errors Task 1 (M=2.2, SD=2.5, SEM=0.5, CI_{95}[1.17, 3.23], N=25)

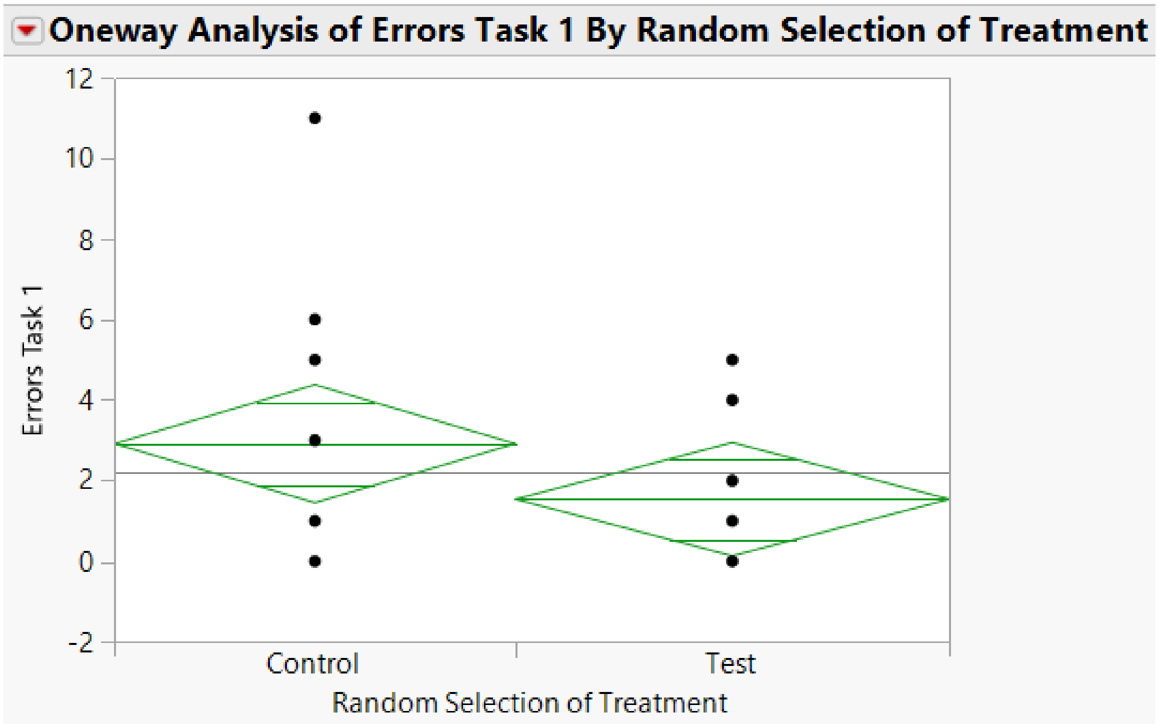


Figure 24. 1-Factor ANOVA of Total Errors for Task 1. Results are not statistically significant but indicate the use of AR have fewer mean errors. (R-square=0.08, DF=24, p-value=0.17)

b. Task 2 (Install Pipe Sleeve)

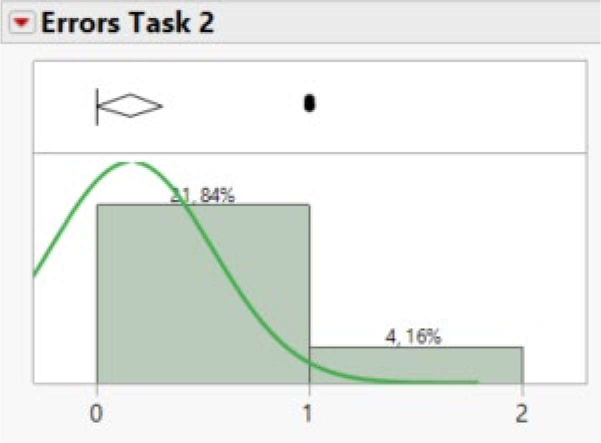


Figure 25. Total Errors Task 2 (M=0.16, SD=0.37, SEM=0.07, CI_{95}[0.006, 0.31], N=25)

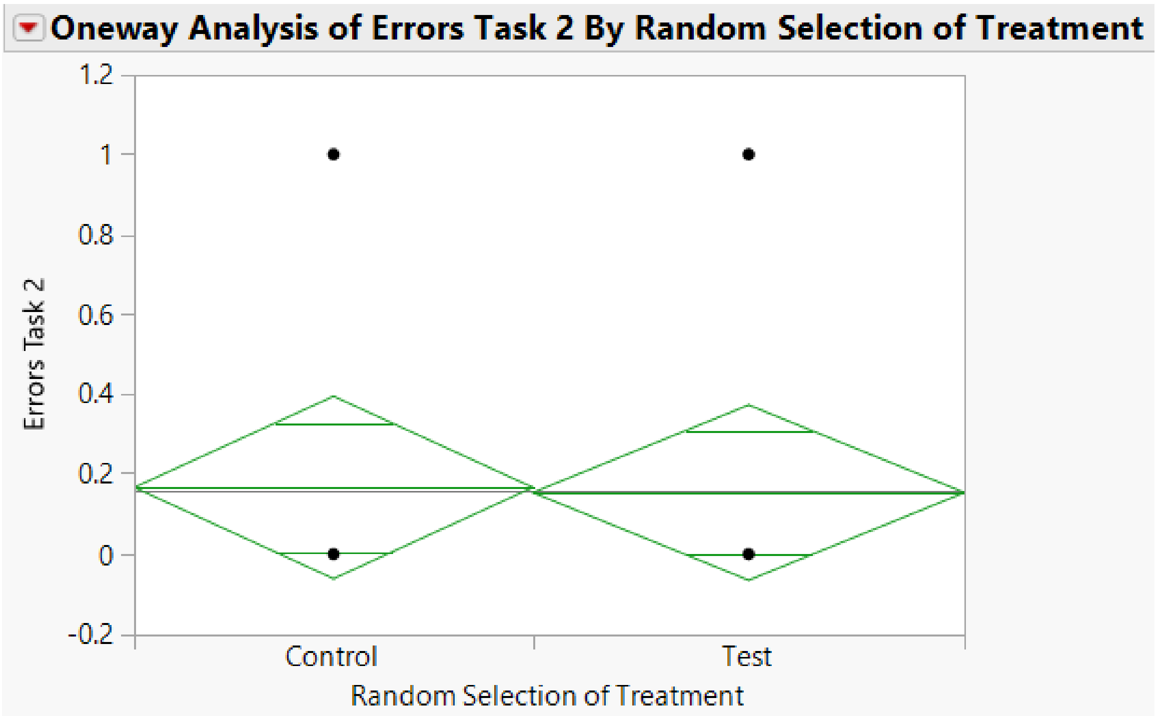


Figure 26. 1-Factor ANOVA of Total Errors for Task 2. Results are not statistically significant and indicate the use of AR has no impact on mean error for task 2. (R-square<0.01, DF=24, p-value=0.93)

c. Task 3 (Assemble Cannon Plug Assembly)

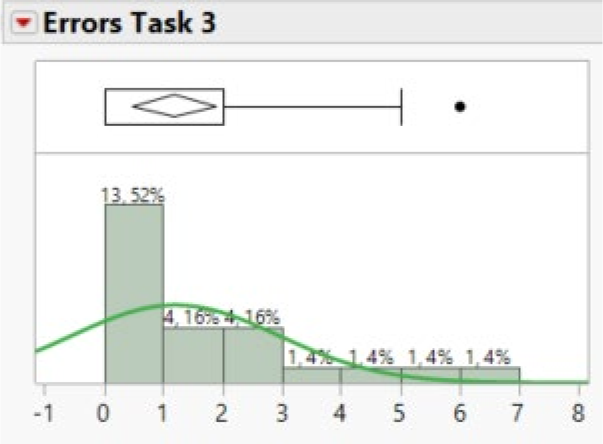


Figure 27. Total Errors Task 3 (M=1.2, SD=1.71, SEM=0.34, CI_{95}[0.50, 1.9], N=25)

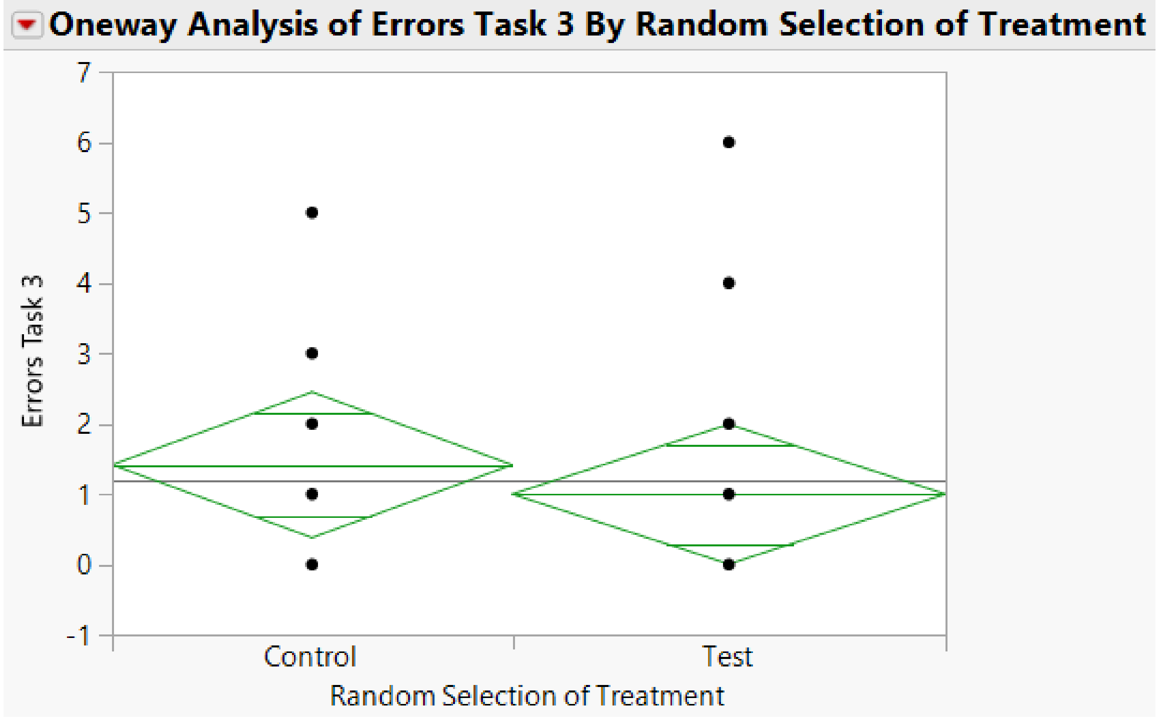


Figure 28. 1-Factor ANOVA of Total Errors for Task 3. Results are not statistically significant and indicate the use of AR has no impact on mean error for task 3. (R-square=0.01, DF=24, p-value=0.55).

d. Task 4 (Inspect Hydraulic Filter)

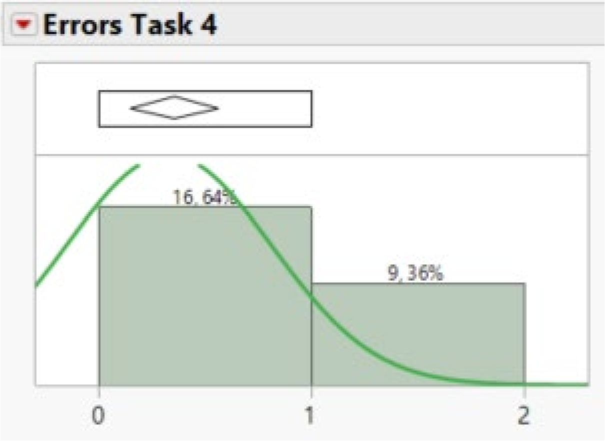


Figure 29. Total Errors Task 4 ($M=0.36$, $SD=0.49$, $SEM=0.10$, $CI_{95}[0.16, 0.56]$, $N=25$).

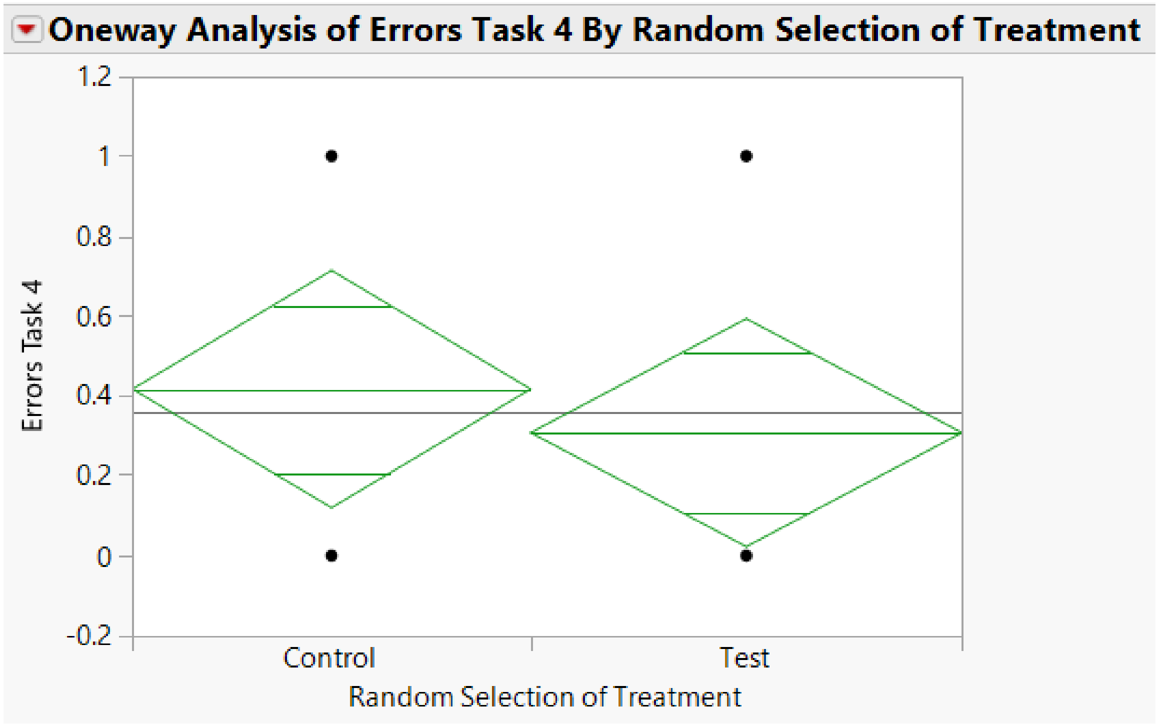


Figure 30. 1-Factor ANOVA of Total Errors for Task 4. Results are not statistically significant but indicate the use of AR have fewer mean errors. (R-square=0.08, DF=24, p-value=0.16).

e. Total Procedure Errors

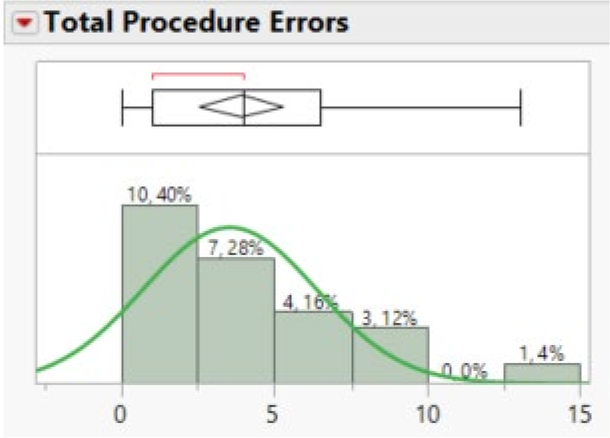


Figure 31. Total Procedure Errors (M=3.92, SD=3.35, SEM=0.67, CI$_{95}$[2.54, 5.3], N=25).

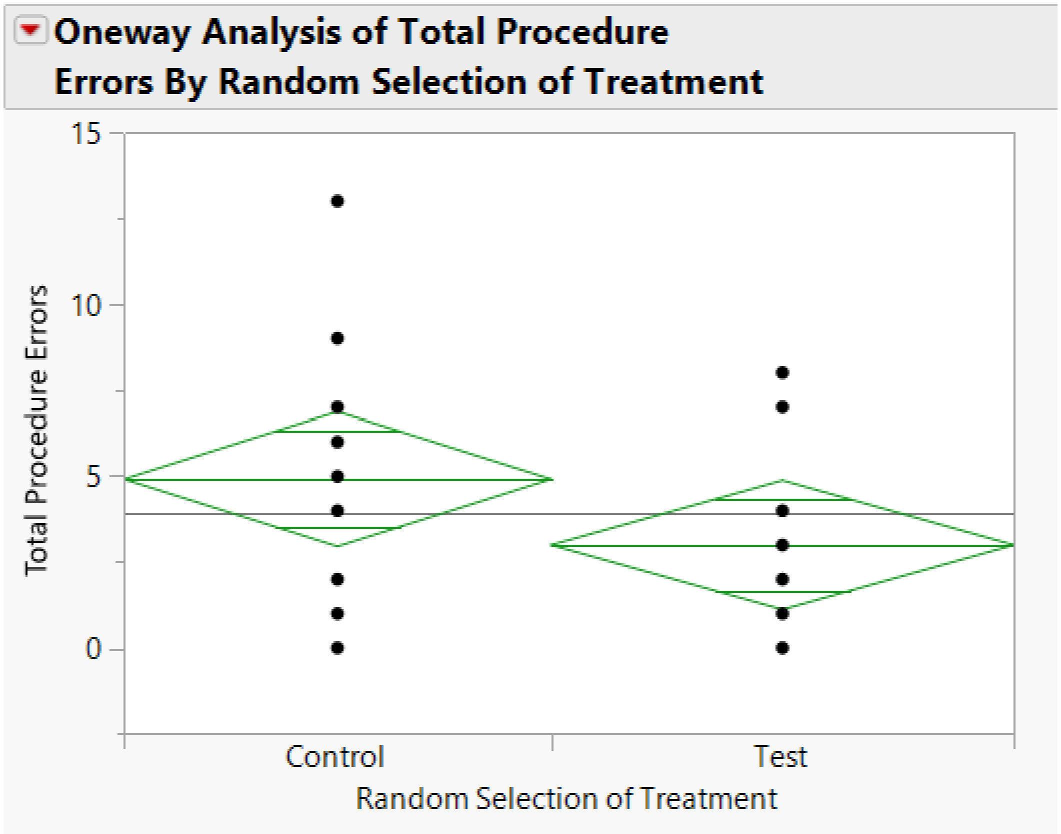
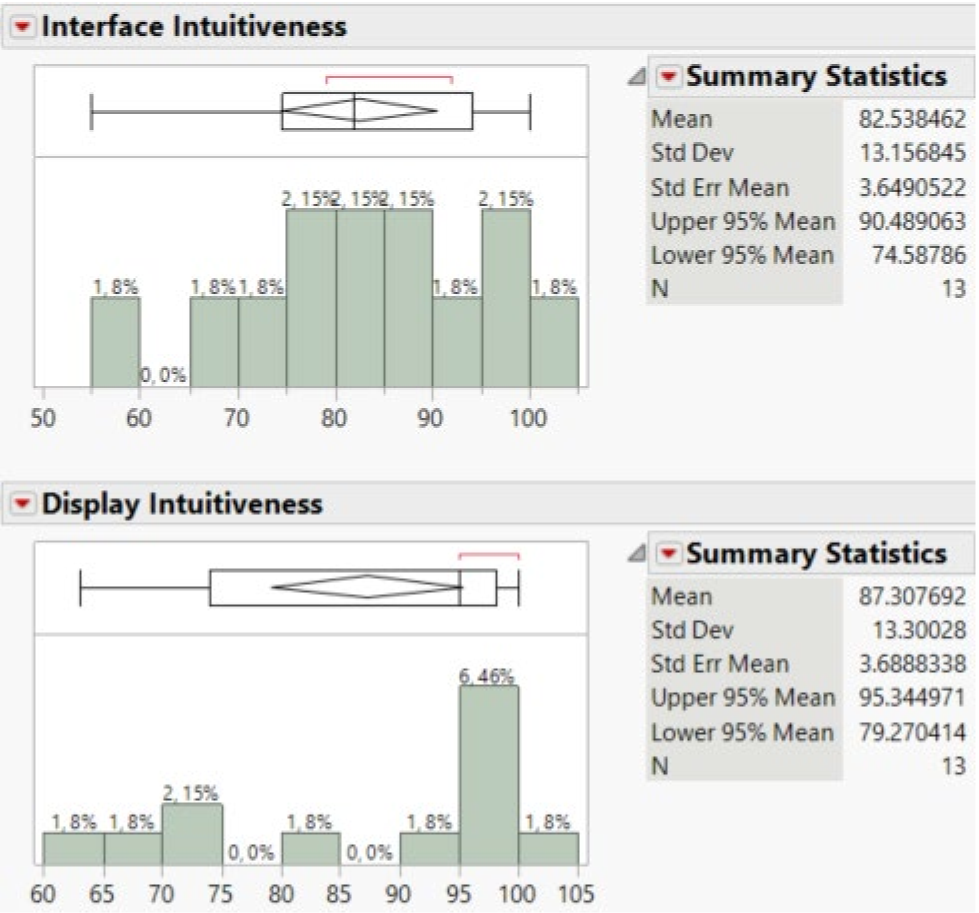


Figure 32. 1-Factor ANOVA of Total Errors for All Tasks. Results are not statistically significant and indicate the use of AR has no impact on mean error for task 3. (R-square=0.01, DF=24, p-value=0.59).

3. Subjective Assessment on Intuitiveness of Task Using Head-Mounted AR

The first subjective measure recorded in the test group was the AR's impact on how intuitive it was for them to interpret the task. Each participant in the test group was given a post-test questionnaire which asked them to mark an "X" on a line to indicate their perceived level of aid the AR contributed in their ability to understand the task. The line was created in such a manner as to not give the participant a numerical suggestion but set at a standard length that their mark on the line could then later be measured on a scale from zero to one hundred. The former being that AR made the task more confusing and the latter being AR had an extreme effect on making the task more intuitive. The user interface of the HoloLens 2 system and the display of the AR projections were independently assessed for level of intuitiveness. The average score for the level of intuitiveness of the HMD interface was equal to 83 out of 100 points. The average score for the level of intuitiveness of the HMD display was valued at 87 out of 100 points.



Interface Intuitiveness

Summary Statistics

Mean	82.538462
Std Dev	13.156845
Std Err Mean	3.6490522
Upper 95% Mean	90.489063
Lower 95% Mean	74.58786
N	13

Display Intuitiveness

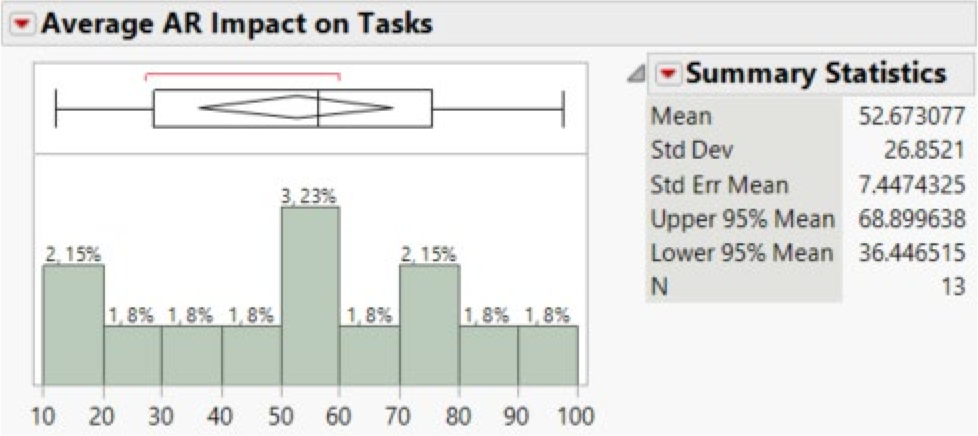
Summary Statistics

Mean	87.307692
Std Dev	13.30028
Std Err Mean	3.6888338
Upper 95% Mean	95.344971
Lower 95% Mean	79.270414
N	13

Figure 33. HMD Interface Distribution (M=82.53, SD=13.16, SEM=3.65, CI_{95}[76.27, 95.34], N=13) and Visual Display Intuitiveness (M=87.31, SD=13.30, SEM=3.69, CI_{95}[79.27, 95.34], N=13).

4. Subjective Assessment on Ease of Task Using Head-Mounted AR

The second subjective measure was assessing the test group's perceived degree of impact that AR had on making the task easier. This scoring system was calculated using the same line method; however, the scoring centered the middle as equal to zero with the left edge of the line equaling negative one hundred and the right edge equaling positive one hundred. The average score for task 1, the panel installation, was equal to 40. The average score for task 2, the pipe sleeve installation, was equal to 53. The average score for task 3, the cannon plug assembly, was equal to 64. The average score for task 4, the hydraulic filter inspection, was equal to 54. The average score across all four tasks was equal to 53 (Figure 34).



Mean	52.673077
Std Dev	26.8521
Std Err Mean	7.4474325
Upper 95% Mean	68.899638
Lower 95% Mean	36.446515
N	13

Figure 34. Perceived Impact on HMD on Task Distribution (M=52.67, SD=26.85, SEM=7.48, CI_{95}[36.45, 68.90], N=13)

B. LIMITATIONS

Much of the numerical data and statistical analysis did not render a statistically significant response. This can be partially attributed to the small sample size of this pilot study. This is due in part to the time-consuming nature of this study as well as the limited body of eligible participants available at the time. Even though the comparisons of difference in means were not statistically significant and their R-values did not suggest a strong explanation of the independent variables, there is a trend that emerges to suggest face validity and encourage better results with a much larger sample size. Typically, observations showed that the mean for task completion time and errors committed was lower for the test group when compared to the control group. Additionally, those with no previous maintenance experience in the test group exhibited a much closer performance to those with maintenance experience than their counterparts in the control group. Continued exploration of this experiment could render a statistically significant result.

While the DRMO parts which were used in this study provided a high degree of realism, they lacked the durability to last the entirety of the study. In task 1, screw number three was too worn to properly get the torque wrench to bite onto the screwhead after participant 6. Therefore, the participants were instructed to omit the torque task of screw 3 after this occurred. After participant 20, the screwheads of the remaining screws were also too worn to allow the torque wrench to properly bite onto the screwhead without applying excessive force and so the torque steps were omitted on these as well. The lower connector for the hydraulic filter was stripped by participant 10, thus task 4 was modified to omit the final seating of the lower connector (step 11). The participants were also informed of this limitation and were instructed they would only need to loosen and tighten the lower connector to the best of their abilities. Since a majority of the participants participated after the connector's thread being stripped and the wearing of screw three, the data collected before these issues were omitted during the analysis. It would be better in the future to have easily replaceable parts that still replicate the actions performed in this study, if it were to be repeated.

One of the major factors of frustration among participants that presented a challenge for the observer was the use of a Phillips-head screwdriver bit to conduct the torque sub-task in task 1. While this device worked during initial testing, it was more difficult than a traditional hex bolt to actually bite and accurately test the torque specifications of the screw. Once the screws were slightly worn, it was impossible to test the torque without putting in a large amount of force behind pressing the driver bit into the screwhead. If this study were to be repeated, it would be advisable to use hexagonal bolts instead of Phillips-head screws. Additionally, having these bolts in a common thread pitch as well as having back up mounting points would also be advisable should a participant accidentally damage a bolt or a mounting thread part way through the study.

An additional limitation worth documenting was the reliability of the HoloLens 2 device during testing. This is not to say the device itself or the experimental process was flawed, but rather that a slight technicality of the software used during testing caused a malfunction with more than two of our test group participants. In these cases, while the participants were conducting the study, the holographic image would disappear and then reappear in another location far away from the referent object. The only solution was to stop the procedure and manually realign the hologram with the physical object before allowing the participant to continue. For one participant this occurred twice. It is suspected this issue was caused by the surrounding environment being too sterile for the HoloLens 2 to properly track its movement in physical space. This could, in theory, be mediated by adding additional textures to the outside of the experimental box and placing the experiment in a room with more textures, objects, and shadows to give the HoloLens 2 additional reference points.

V. DISCUSSION, FUTURE RESEARCH, AND CONCLUSION

A. DISCUSSION

This research did not find a statistically significant difference between the conditions of completing maintenance tasks in a visually occluded area with and without the use of AR. Neither the times for each task nor the TPT significantly differ statistically, regardless of independent variable group placement, amongst the participants. Additionally, the same observation was made for the TNE amongst both groups. For this reason, we cannot reject the null hypothesis in favor of the alternative for speed and accuracy of task completion. These results are believed to be predominately due to small sample size combined with a high degree of variance between participants in both TPT and TNE. The only statistically significant observations were the perception by the participants in the test group claiming the AR made each task subjectively easier and more intuitive.

A summary of the speed statistics for each task examined can be found in Table 1. The p-value for all tasks were greater than or equal to 0.29, showing no evidence of statistical significance. The R-Squared statistic for each task is also at or below 0.05, suggesting the testing condition had very little impact on the results with the current model and low number of participants. Task 1 saw a high degree of variance due to most participants having difficulty appropriately using the torque wrench to torque the screws. This caused a considerable number of participants to spend an excess amount of time on this test, especially towards the end of the experiment. Despite not showing statistical significance, the test group completed the task on average 137 seconds, or 15 percent faster than the control group. Task 2 appears to suggest that the testing condition had less of an impact than in task 1 with a p-value of 0.42. The average completion time for the test condition was still shorter with an average time of 78 seconds, or 13 percent faster than the control. This trend continues with task 3, having a p-value of 0.3 but showing the test condition conducted the task in 52 seconds, or 15 percent faster than the control. Task 4, with a p-value of 0.7, shows the smallest impact with only a 24 second, or 6 percent difference between groups. Cumulatively, the procedure was completed in 291 seconds, or 13 percent faster in the test group. This suggests there was a cumulative effect occurring in the test group, with the largest impact being on the panel installation task and the cannon plug assembly task. While this suggests face validity, at present, we cannot determine if this was due to AR or some other factor.

Table 1. Speed Statistics

	Mean Time	95% CI for Time	P-value	R-value
Task 1	837.8sec	700.40, 975.19sec	0.31	0.04
Task 2	577.44sec	479.43, 675.45sec	0.42	0.03
Task 3	307.44sec	257.46, 357.42sec	0.3	0.05
Task 4	383.88sec	320.60, 447.15sec	0.7	< 0.01
Complete Procedure	2106.56sec	1836.09, 2377.03sec	0.29	0.05

Both sequence errors and performance errors for each step were recorded when calculating the total errors per task. In some cases, an initial error could have a cascading effect on subsequent steps, but in most cases each step was unique unto itself. This is why in some tasks we see a higher mean error than in others. Table 2 depicts the summary statistics for the overall accuracy performance of the participants during the experiment. Task 1 saw a mean error difference of 2.92 for the control group and 1.54 for the test group, or a mean error difference of 1.38 between groups. Only four errors were committed by four different participants on three different steps for task 2. This provides us with very little data to form any rational conclusion to suggest AR had an impact on the participant's ability to install a pipe sleeve. The mean error for the control group on task 3 was 1.42 while the test group mean was 1.00. The mean error for the control group on task 4 was 0.42 while the test group mean was 0.31. Neither task 3 nor task 4 show any strong relationship with a p-value of 0.55 and 0.59, respectively. The complete procedure demonstrates the strongest relationship with a p-value of 0.16. The mean error difference between groups was 1.92 with the control group mean at 4.92 and the test group mean at 3.00. This evidence shows the test group consistently was more accurate, but it does not currently prove that this was due to the testing condition. It is worth noting that the types of errors committed by groups was often different. For example, an error in task 3 is defined as either not properly seating the cannon plug or putting the plugs in the wrong location.

For the control group, both cases occurred. For the test group, the only errors committed were due to the participant not fully seating the cannon plug into position. This suggests that the AR device is still aiding them in situational awareness, more so than without having the device.

Table 2. Accuracy Statistics

	Mean Errors	95% CI for Errors	P-value	R-value
Task 1	2.2	1.17, 3.23	0.17	0.08
Task 2	0.16	0.006, 0.31	0.93	< 0.01
Task 3	1.2	0.50, 1.9	0.55	0.01
Task 4	0.36	0.16, 0.56	0.59	0.01
Complete Procedure	3.92	2.54, 5.3	0.16	0.08

It comes as no surprise that having prior maintenance experience showed a significant improvement on performance, however, having prior AR experience did not seem to effect task speed or accuracy (Figure 35). Using a pooled t-test, it was found that having prior maintenance experience was statistically significant in TPT with a p-value equal to 0.031, and on TNE with a p-value equal to 0.036. Even though the AR results were not statistically significant, they still demonstrated some consistent trends of the test group outperforming the control group in speed and accuracy as can be seen by Figure 36. While these results suggest the test condition does not have a significant improvement for participants with prior maintenance experience when it comes to TPT and TNE, it does show improvement in participants with no maintenance experience by bringing their performance metrics closer to those with prior experience (Figure 35). This suggests at least visually that using AR in this data set has improved novice maintainer performance to be on par with experienced maintenance performance.

Figure 35. Graph of the Total Procedure Time and Errors vs. Maintenance Experience with Overlay Depicting the Use of AR (red) vs. No Use of AR (blue).

Figure 36. Graph of the Total Procedure Time and Errors vs. Testing Condition with Maintenance Experience (yes) in Red, and No Maintenance Experience (no) in Blue.

Amongst the test group, the general perception was that the AR device significantly improved their ability to understand the task and reduce cognitive load with a lower 95% confidence mean of 74.59 for interface intuitiveness and 79.27 for display intuitiveness. While it is difficult to determine what the overall significance this score has just off the data provided, it combined with their post-test questionnaire comments would suggest that most participants had little trouble using the AR device within this scenario. Many verbally noted they found the device easy to use and understand, and some even noted they did not require the additional information provided by the written instructions and 2D animations displayed on the computer except in few cases where they needed to review a previous step. This means that the use of AR devices can be used as a means of instruction for a novice user to understand and utilize the technology. With the scale of the AR device's impact on performance of task being between -100 and 100, the mean score of 52.67 suggests that the participants perceived the tasks as easier to conduct with the assistance of the AR device. Only two participants scored the AR device as having little or no effect on reducing the difficulty of the tasks, making them outliers from the majority. For one of these cases, the user was having desyncing issue with the HMD which may have influenced their decision. It may also be that they could have been overstimulated by the AR when combined with the written and audio instructions, and the 2D animations, as some participants noted.

An additional observation worth noting is that most participants in the control group focused primarily on the 2D visual animation for spatial reasoning and the audio for specific instructions. Few participants put much emphasis on the written instructions. Many did not pay attention to the diagrams and schematics of the objects in the written instructions. In the test group, similar behavior was observed, albeit a little differently. The exception being some of them stated they focused solely on the HoloLens AR imagery and audio instead of the 2D animations, or they initially viewed the 2D animation and then used the AR imagery while conducting the task. Since most participants tuned out the written instructions and focused solely on the audio instructions and AR for visual aid, perhaps a better litmus test would be to give the control group only the written instructions of the maintenance tasks with 2D static imagery and give the test group only the audio instructions and AR animations. This would be a more accurate comparison between current industry practices used by the Navy's maintenance community and AR's capabilities. It is possible that since most participants were not familiar with AR, having an instructional method most people are already familiar with (i.e., the 2D animations) present in the test group could have pulled their attention from the AR imagery, especially if the 2D animation was observed before they saw the AR projection. This could in turn negatively impact the perceived level of aid the participants felt was given by the HMD. This further reinforces the suggestion that future studies examine current industry practices directly to AR-only instructional methods.

The AR instructions did not affect all types of tasks equally. Some tasks were aided better than others when it comes to speed and accuracy. The prevailing trend was that in tasks which require lengthy manipulation of the object, such as a screwing task, the AR only helped the participant initially index to the object, but it did not aid in the completion of the manipulation. Some participants stated the continuous animation from the AR device conflicted with their proprioception during these types of lengthy manipulations, causing them to need to look away to focus on manipulating the object. This behavior was also observed by the observer, as many participants in both groups initially looked at the referent object on approach, then their gaze relaxed to a more neutral position looking forward while they manipulated the object. On the other hand, simple, quick manipulations often resulted in the participant strongly focused on the AR projection during the manipulation of the object, such as when installing cannon plugs. Upon reflection of this experiment, it is observed that when combining small sample size with few long, complex tasks therein creates a difficulty in the ability to decern what causes the results of the experiment. A better method would be to make the tasks shorter, easier, and with fewer variables on how they could be completed.

B. FUTURE RESEARCH

This experiment is limited in that it only examines the interaction of a single human using a single device to work on a single object at a time in a controlled environment. It is our belief that this study reinforces the suggestions of Angelopoulos, Engelke, Tang, Wang, and Webel and their associates and supports maturing AR for the purpose of creating improved methodologies for conducting complex maintenance tasks. As the technology currently sits, this technique is laborious in its creation and its inherit complexity reduces its reliability when compared to traditional methods. Additional work will need to be done to fully mature this technology. It is my recommendation that future research focus on the following areas of interest:

- Explore and mature hand tracking technology to include visual information.
- Explore and mature tool tracking technology to include visual information.
- Because this research showed AR provided different levels of assistance to different tasks, specific use-cases for using AR in occluded tasks need to be examined to discover which provide most value.
- Continue to mature and optimize AR instructional methods to reduce cognitive load while improving efficiency and precision.
- Mature the ability to implement a remote expert guidance method using available AR technology.
- Once a methodology for AR instructions is optimized, create a method for interoperability between systems using local and board networking architectures.
- Once a methodology for AR instructions is optimized, create a method to provide live data tracking that enables the maintainer's performance to be instantly documented and logged for job completion. This capability would need to be a user-traceable, passive approach which adds as little impact on the user as possible.
- Conduct additional research to understand the impact a real-world environment or field conditions would have on the same type of study.

In addition to this technology being matured in its ability to create specific instructional methods, development should simultaneously be matured to produce interoperable solutions to automatically update administrative systems. This would turn a currently active and burdensome process into a nearly automated process. This adds the benefit of not only reducing the cognitive burden on the maintainer, but it would also reduce their overall skill requirements of the maintainer as well as increase turnaround time to complete tasks. Though this technology is still in its infancy, this is where the groundwork can be laid to revolutionize the way aviation maintenance is instructed, conducted, and documented. From a system's perspective, the maturation of the suggestions above offers the opportunity to automate many procedures and make them work in parallel. This gives the potential to provide a large evolutionary step in the way the DOD conducts aviation maintenance and bring it to the bleeding edge of 21st century technology.

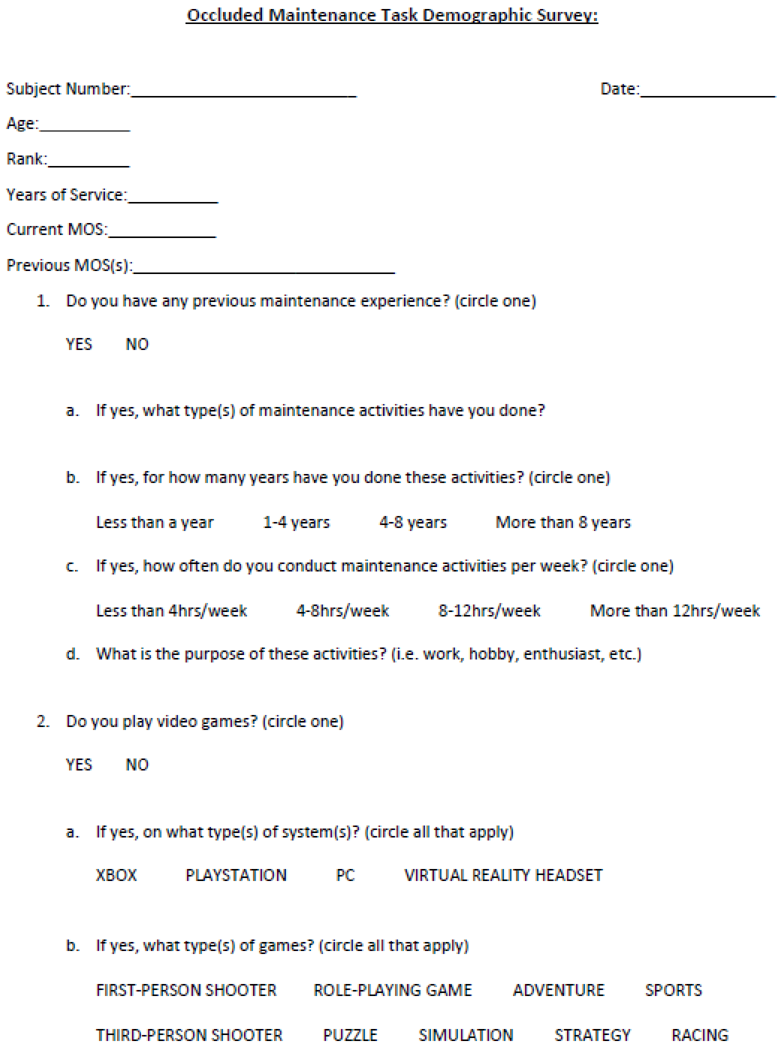
C. CONCLUSION

The proper utilization and potential solutions for AR are still not fully understood. This thesis sought to provide a means of using AR to solve current aviation maintenance issues by demonstrating that it can reduce cognitive load, make procedures easier to understand, and ultimately make the novice user more capable by being faster and more accurate. While the statistical analysis in this study does not objectively demonstrate that AR is faster or more accurate, it does suggest that a relationship in increased performance exists between a novice maintainer using AR versus not using AR.

The test group participants of this study believe that AR is easy to understand and aids in their ability to complete complex tasks. Belief has a very strong impact on real-world human performance. As we attempt to avoid stagnation and exploit emerging technologies, we owe it to our servicemembers to continue to mature this technology. We must find where it fits into the overall picture and where it does not. With additional research which modifies the variables used in this study and the ones it references, we can answer this question and further bolster the observations that AR has a future of being a force multiplier in our aviation maintenance community.

APPENDIX

A. PRE-TEST DEMOGRAPHIC QUESTIONNAIRE



Occluded Maintenance Task Demographic Survey:

Subject Number:______________________ Date:_____________

Age:_________

Rank:________

Years of Service:_________

Current MOS:__________

Previous MOS(s):_________________________

1. Do you have any previous maintenance experience? (circle one)

   YES NO

   a. If yes, what type(s) of maintenance activities have you done?

   b. If yes, for how many years have you done these activities? (circle one)

      Less than a year 1-4 years 4-8 years More than 8 years

   c. If yes, how often do you conduct maintenance activities per week? (circle one)

      Less than 4hrs/week 4-8hrs/week 8-12hrs/week More than 12hrs/week

   d. What is the purpose of these activities? (i.e. work, hobby, enthusiast, etc.)

2. Do you play video games? (circle one)

   YES NO

   a. If yes, on what type(s) of system(s)? (circle all that apply)

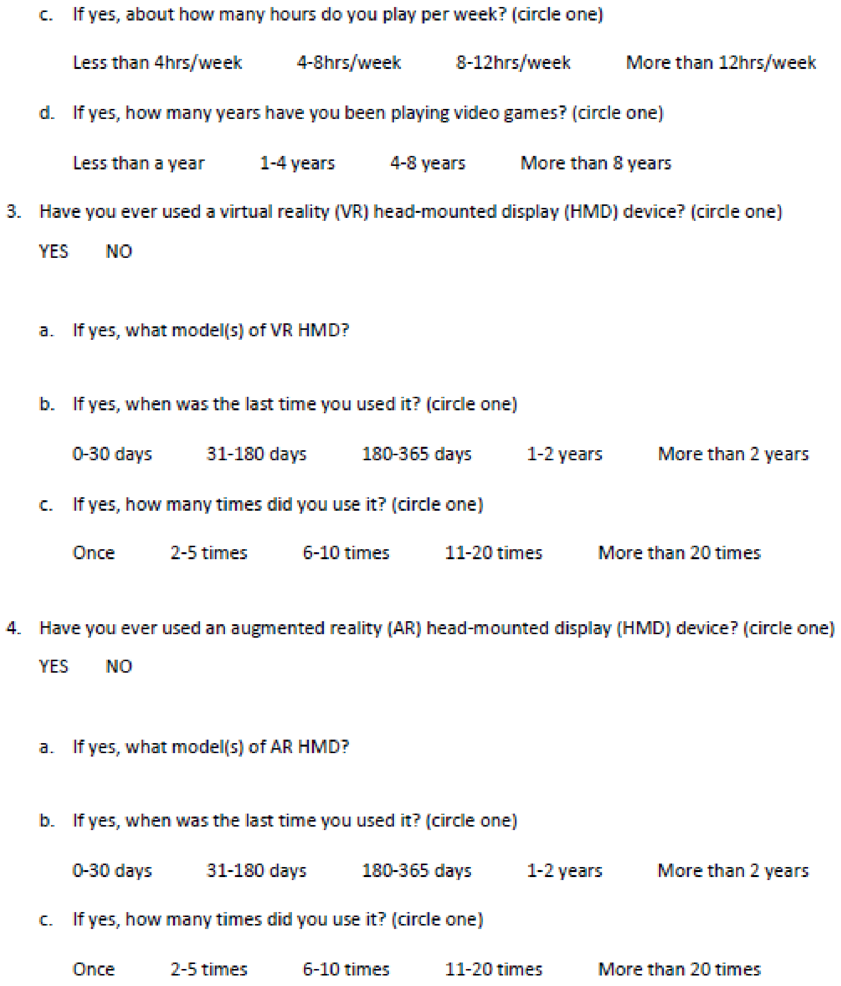
      XBOX PLAYSTATION PC VIRTUAL REALITY HEADSET

   b. If yes, what type(s) of games? (circle all that apply)

      FIRST-PERSON SHOOTER ROLE-PLAYING GAME ADVENTURE SPORTS

      THIRD-PERSON SHOOTER PUZZLE SIMULATION STRATEGY RACING

Figure 37. Demographic Survey, page 1



c. If yes, about how many hours do you play per week? (circle one)

Less than 4hrs/week   4-8hrs/week   8-12hrs/week   More than 12hrs/week

d. If yes, how many years have you been playing video games? (circle one)

Less than a year   1-4 years   4-8 years   More than 8 years

3. Have you ever used a virtual reality (VR) head-mounted display (HMD) device? (circle one)

YES   NO

a. If yes, what model(s) of VR HMD?

b. If yes, when was the last time you used it? (circle one)

0-30 days   31-180 days   180-365 days   1-2 years   More than 2 years

c. If yes, how many times did you use it? (circle one)

Once   2-5 times   6-10 times   11-20 times   More than 20 times

4. Have you ever used an augmented reality (AR) head-mounted display (HMD) device? (circle one)

YES   NO

a. If yes, what model(s) of AR HMD?

b. If yes, when was the last time you used it? (circle one)

0-30 days   31-180 days   180-365 days   1-2 years   More than 2 years

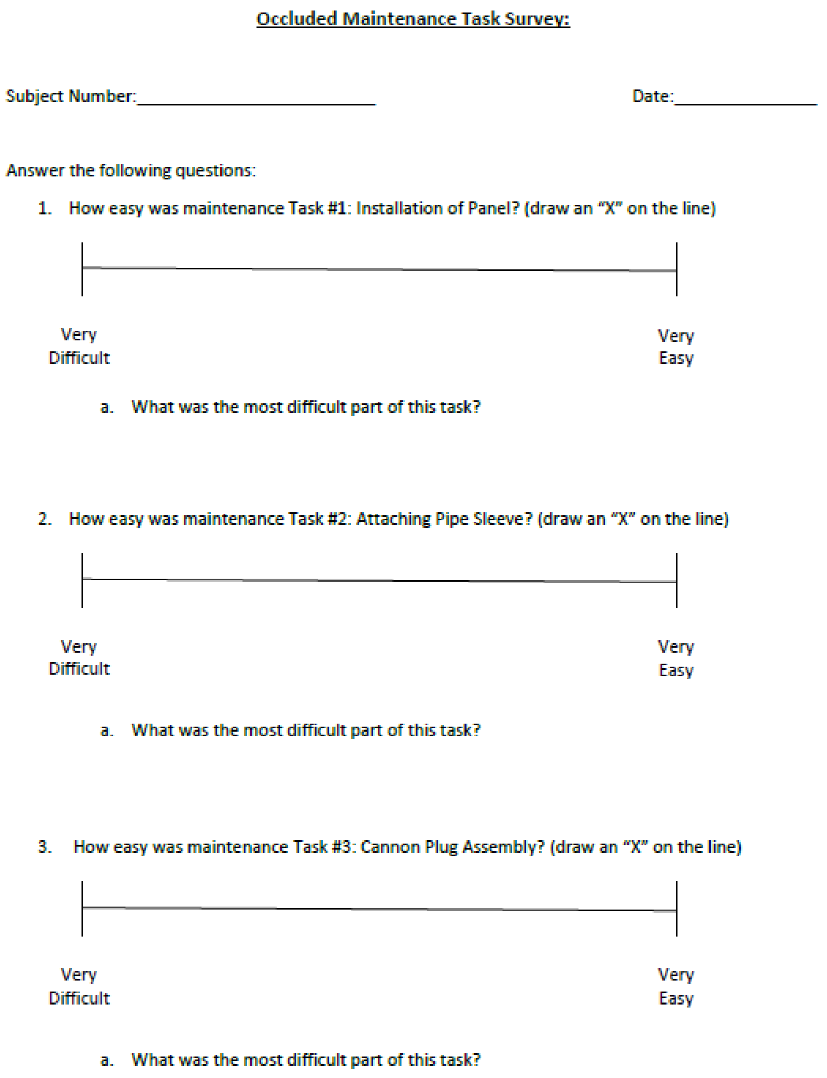
c. If yes, how many times did you use it? (circle one)

Once   2-5 times   6-10 times   11-20 times   More than 20 times

Figure 38. Demographic Survey, page 2

B. POST-TEST QUESTIONNAIRES

1. Control Group Questionnaire



Occluded Maintenance Task Survey:

Subject Number:________________________

Date:______________

Answer the following questions:

1. How easy was maintenance Task #1: Installation of Panel? (draw an "X" on the line)

   Very Difficult — Very Easy

   a. What was the most difficult part of this task?

2. How easy was maintenance Task #2: Attaching Pipe Sleeve? (draw an "X" on the line)

   Very Difficult — Very Easy

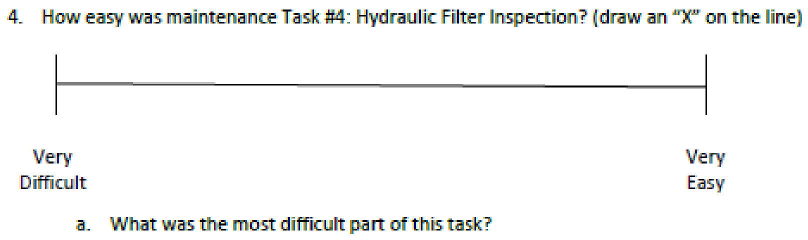
   a. What was the most difficult part of this task?

3. How easy was maintenance Task #3: Cannon Plug Assembly? (draw an "X" on the line)

   Very Difficult — Very Easy

   a. What was the most difficult part of this task?

Figure 39. Control Group Post-test Questionnaire, page 1



4. How easy was maintenance Task #4: Hydraulic Filter Inspection? (draw an "X" on the line)

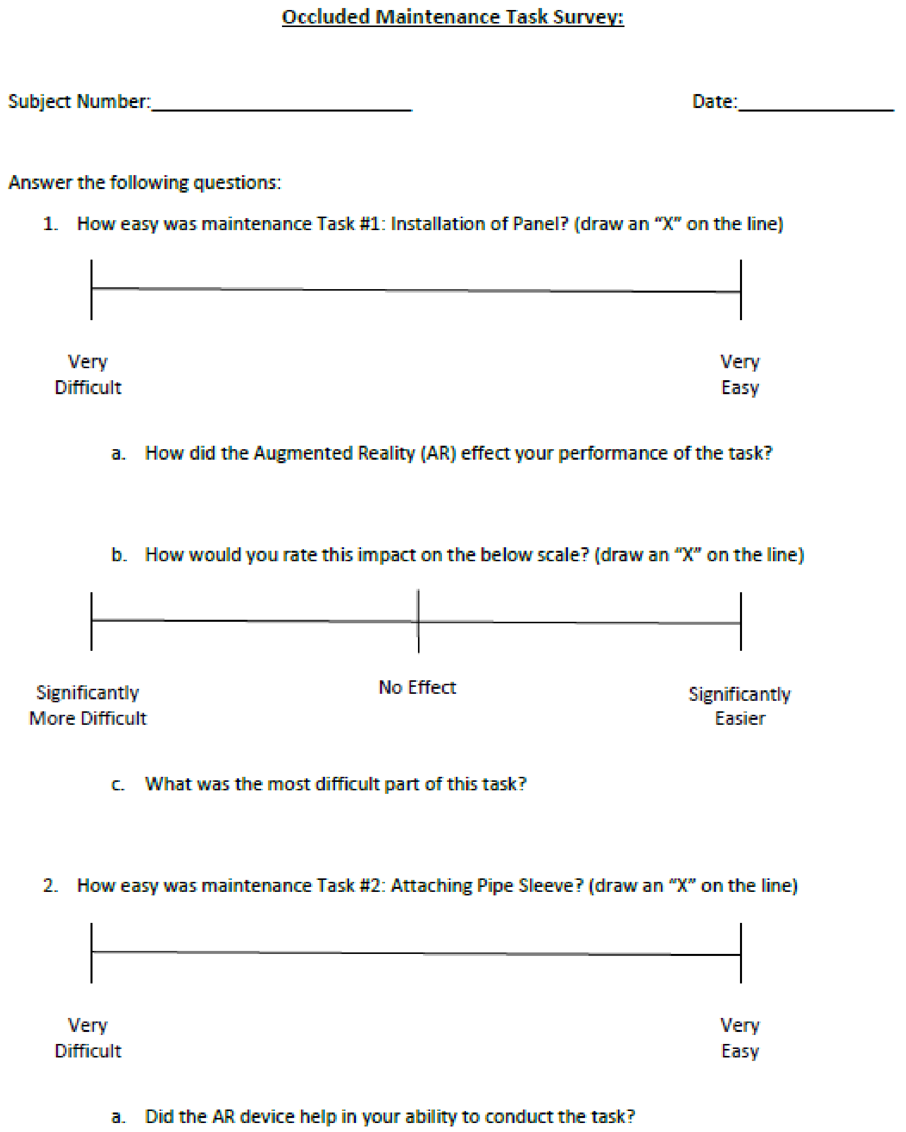
Very Difficult

Very Easy

a. What was the most difficult part of this task?

Figure 40. Control Group Post-test Questionnaire, page 2

2. Test Group Questionnaire



Occluded Maintenance Task Survey:

Subject Number:________________________ Date:______________

Answer the following questions:

1. How easy was maintenance Task #1: Installation of Panel? (draw an "X" on the line)

Very Difficult ——— Very Easy

   a. How did the Augmented Reality (AR) effect your performance of the task?

   b. How would you rate this impact on the below scale? (draw an "X" on the line)

Significantly More Difficult ——— No Effect ——— Significantly Easier

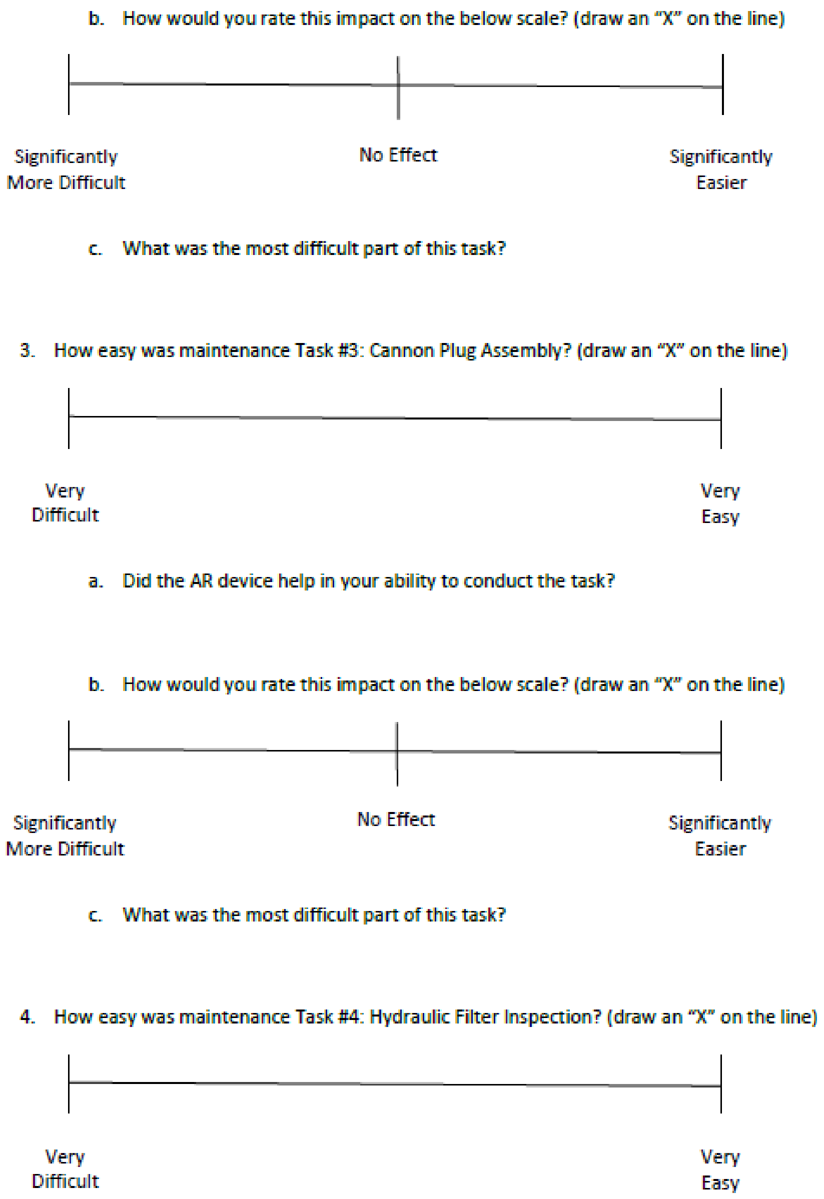
   c. What was the most difficult part of this task?

2. How easy was maintenance Task #2: Attaching Pipe Sleeve? (draw an "X" on the line)

Very Difficult ——— Very Easy

   a. Did the AR device help in your ability to conduct the task?

Figure 41. Test Group Post-test Questionnaire, page 1



b. How would you rate this impact on the below scale? (draw an "X" on the line)

Significantly More Difficult
No Effect
Significantly Easier

c. What was the most difficult part of this task?

3. How easy was maintenance Task #3: Cannon Plug Assembly? (draw an "X" on the line)

Very Difficult
Very Easy

a. Did the AR device help in your ability to conduct the task?

b. How would you rate this impact on the below scale? (draw an "X" on the line)

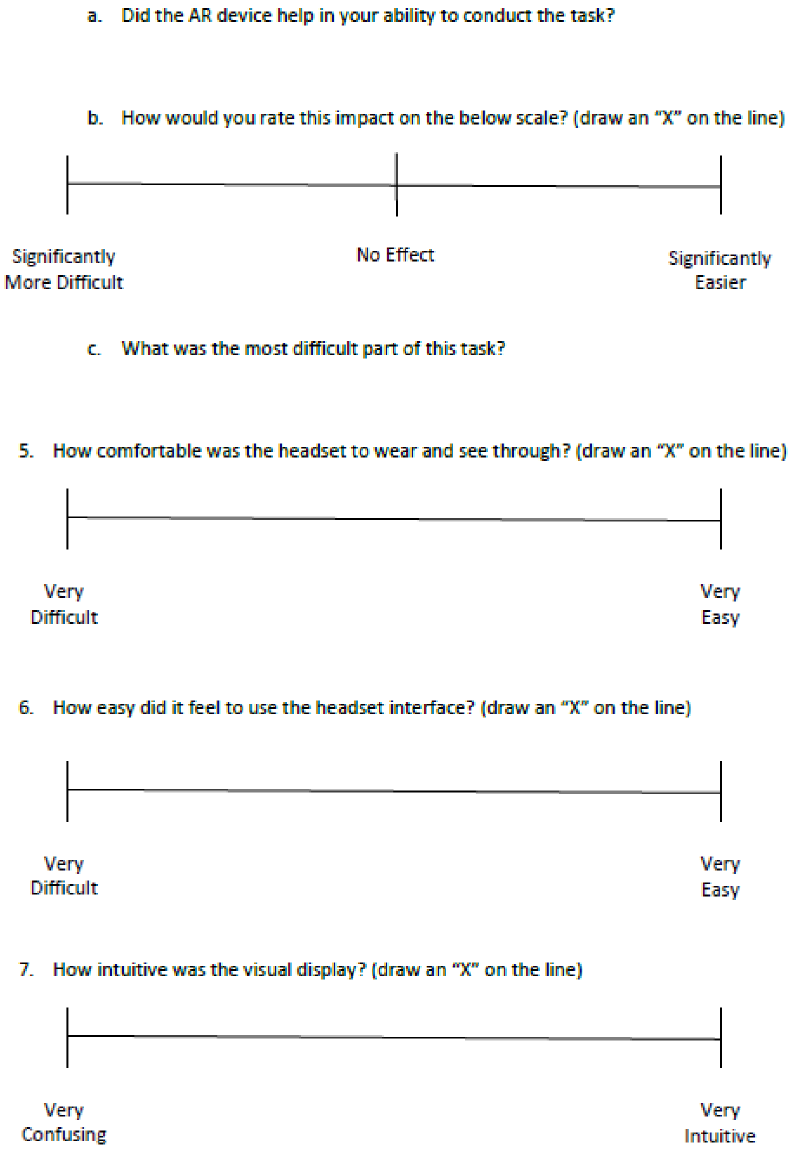
Significantly More Difficult
No Effect
Significantly Easier

c. What was the most difficult part of this task?

4. How easy was maintenance Task #4: Hydraulic Filter Inspection? (draw an "X" on the line)

Very Difficult
Very Easy

Figure 42. Test Group Post-test Questionnaire, page 2



a. Did the AR device help in your ability to conduct the task?

b. How would you rate this impact on the below scale? (draw an "X" on the line)

Significantly More Difficult | No Effect | Significantly Easier

c. What was the most difficult part of this task?

5. How comfortable was the headset to wear and see through? (draw an "X" on the line)

Very Difficult | Very Easy

6. How easy did it feel to use the headset interface? (draw an "X" on the line)

Very Difficult | Very Easy

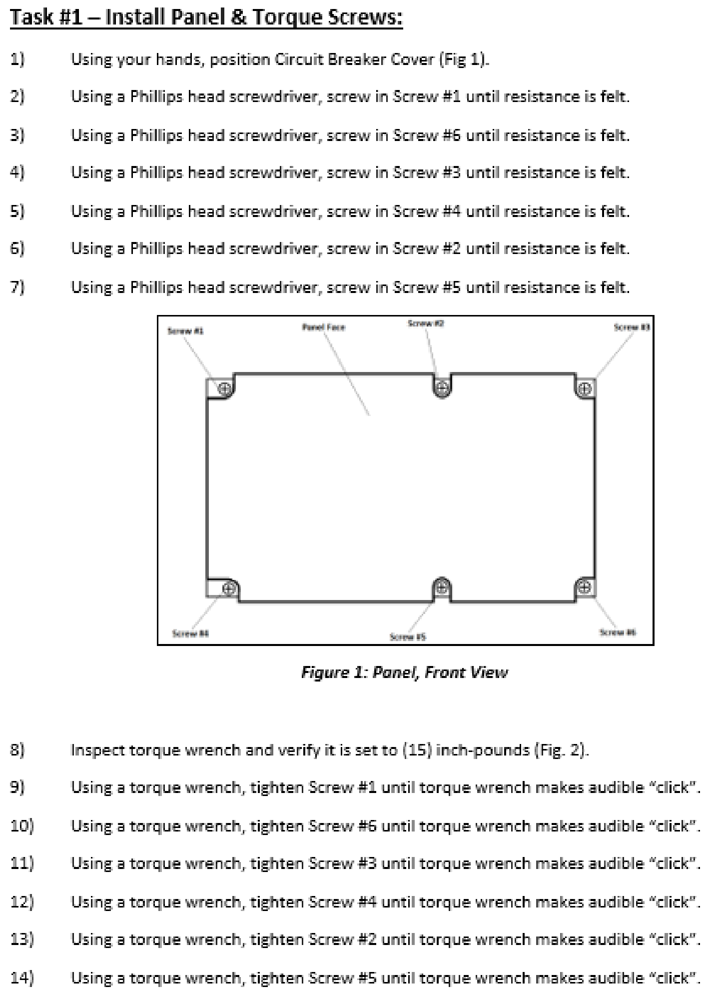
7. How intuitive was the visual display? (draw an "X" on the line)

Very Confusing | Very Intuitive

Figure 43. Test Group Post-test Questionnaire, page 3

C. TASK INSTRUCTIONS

1. Task 1 (Installation of Panel and Torquing of Screws)



Task #1 – Install Panel & Torque Screws:

1) Using your hands, position Circuit Breaker Cover (Fig 1).
2) Using a Phillips head screwdriver, screw in Screw #1 until resistance is felt.
3) Using a Phillips head screwdriver, screw in Screw #6 until resistance is felt.
4) Using a Phillips head screwdriver, screw in Screw #3 until resistance is felt.
5) Using a Phillips head screwdriver, screw in Screw #4 until resistance is felt.
6) Using a Phillips head screwdriver, screw in Screw #2 until resistance is felt.
7) Using a Phillips head screwdriver, screw in Screw #5 until resistance is felt.

Figure 1: Panel, Front View

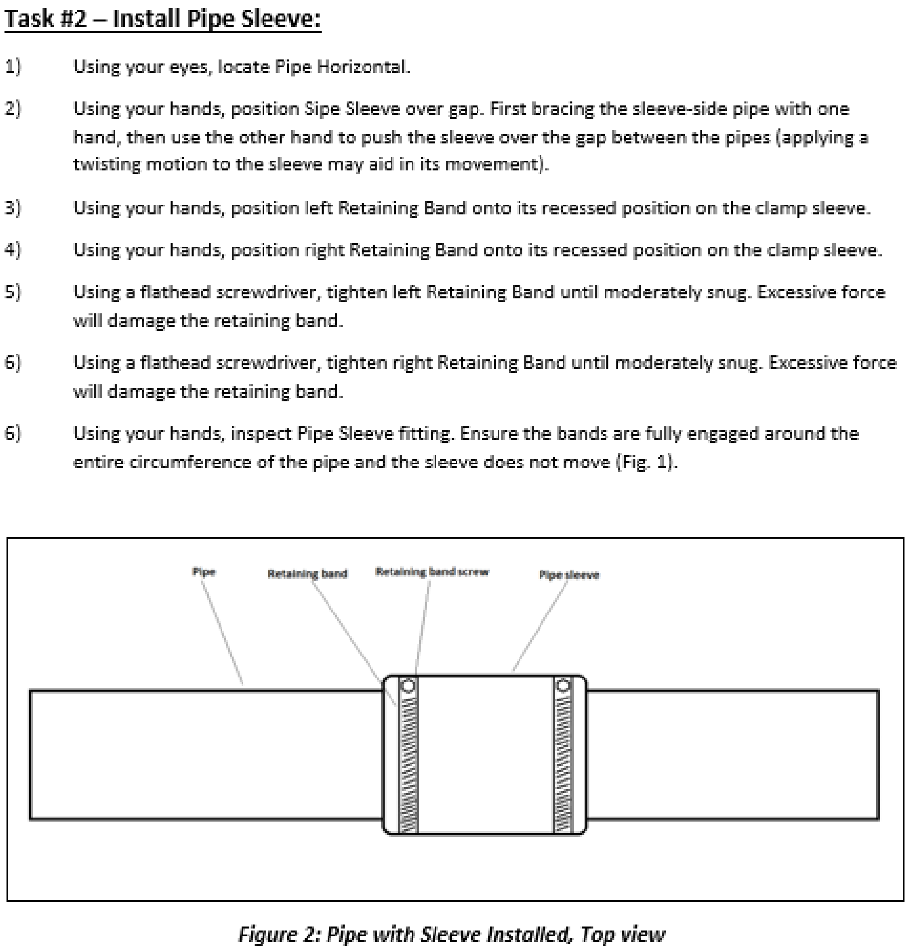
8) Inspect torque wrench and verify it is set to (15) inch-pounds (Fig. 2).
9) Using a torque wrench, tighten Screw #1 until torque wrench makes audible "click".
10) Using a torque wrench, tighten Screw #6 until torque wrench makes audible "click".
11) Using a torque wrench, tighten Screw #3 until torque wrench makes audible "click".
12) Using a torque wrench, tighten Screw #4 until torque wrench makes audible "click".
13) Using a torque wrench, tighten Screw #2 until torque wrench makes audible "click".
14) Using a torque wrench, tighten Screw #5 until torque wrench makes audible "click".

Figure 44. Task 1 Written Instructions, page 1

Figure 2: Torque Wrench Setting

Figure 45. Task 1 Written Instructions, page 2

2. Task 2 (Installation of Pipe Sleeve)



Task #2 – Install Pipe Sleeve:

1) Using your eyes, locate Pipe Horizontal.

2) Using your hands, position Sipe Sleeve over gap. First bracing the sleeve-side pipe with one hand, then use the other hand to push the sleeve over the gap between the pipes (applying a twisting motion to the sleeve may aid in its movement).

3) Using your hands, position left Retaining Band onto its recessed position on the clamp sleeve.

4) Using your hands, position right Retaining Band onto its recessed position on the clamp sleeve.

5) Using a flathead screwdriver, tighten left Retaining Band until moderately snug. Excessive force will damage the retaining band.

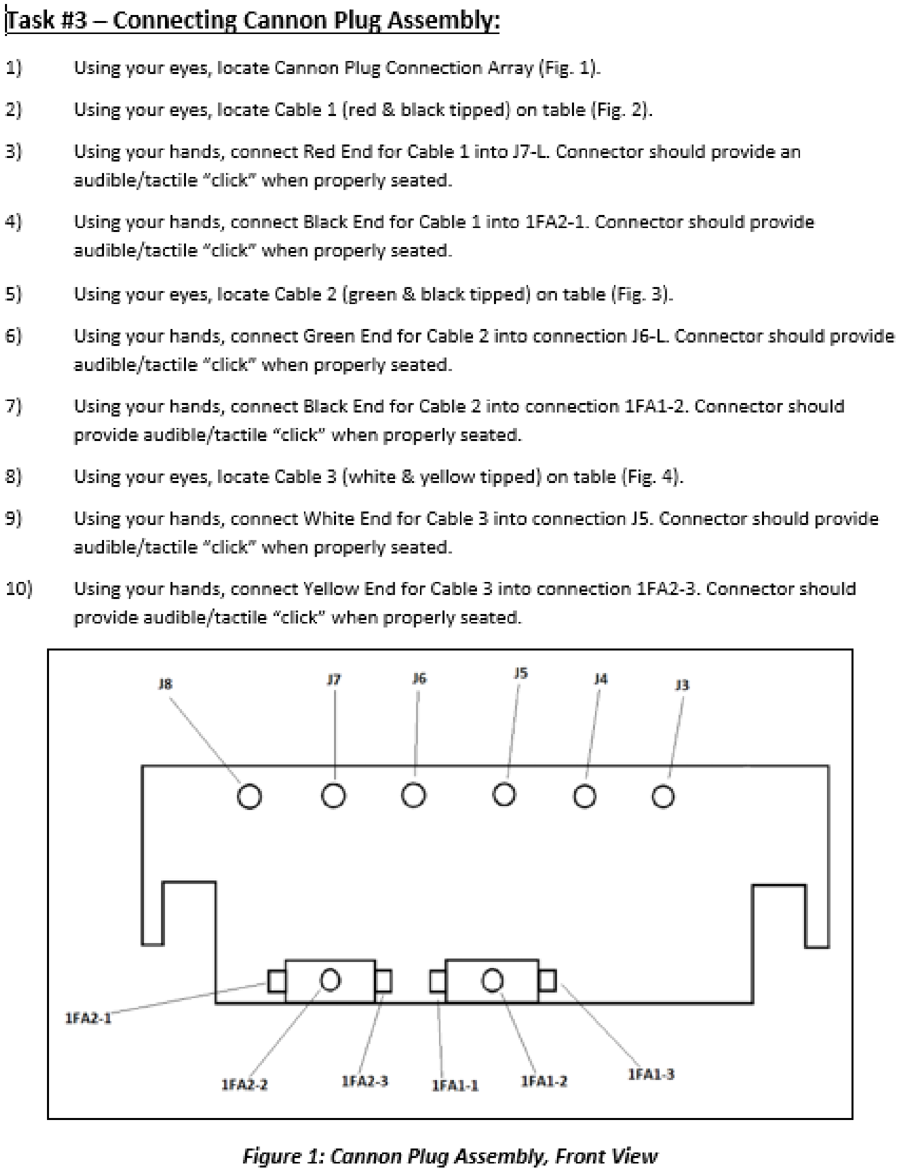
6) Using a flathead screwdriver, tighten right Retaining Band until moderately snug. Excessive force will damage the retaining band.

6) Using your hands, inspect Pipe Sleeve fitting. Ensure the bands are fully engaged around the entire circumference of the pipe and the sleeve does not move (Fig. 1).

Figure 2: Pipe with Sleeve Installed, Top view

Figure 46. Task 2 Written Instructions

3. Task 3 (Assembly of Cannon Plugs)



Task #3 – Connecting Cannon Plug Assembly:

1) Using your eyes, locate Cannon Plug Connection Array (Fig. 1).
2) Using your eyes, locate Cable 1 (red & black tipped) on table (Fig. 2).
3) Using your hands, connect Red End for Cable 1 into J7-L. Connector should provide an audible/tactile "click" when properly seated.
4) Using your hands, connect Black End for Cable 1 into 1FA2-1. Connector should provide audible/tactile "click" when properly seated.
5) Using your eyes, locate Cable 2 (green & black tipped) on table (Fig. 3).
6) Using your hands, connect Green End for Cable 2 into connection J6-L. Connector should provide audible/tactile "click" when properly seated.
7) Using your hands, connect Black End for Cable 2 into connection 1FA1-2. Connector should provide audible/tactile "click" when properly seated.
8) Using your eyes, locate Cable 3 (white & yellow tipped) on table (Fig. 4).
9) Using your hands, connect White End for Cable 3 into connection J5. Connector should provide audible/tactile "click" when properly seated.
10) Using your hands, connect Yellow End for Cable 3 into connection 1FA2-3. Connector should provide audible/tactile "click" when properly seated.

Figure 1: Cannon Plug Assembly, Front View

Figure 47. Task 3 Written Instructions, page 1

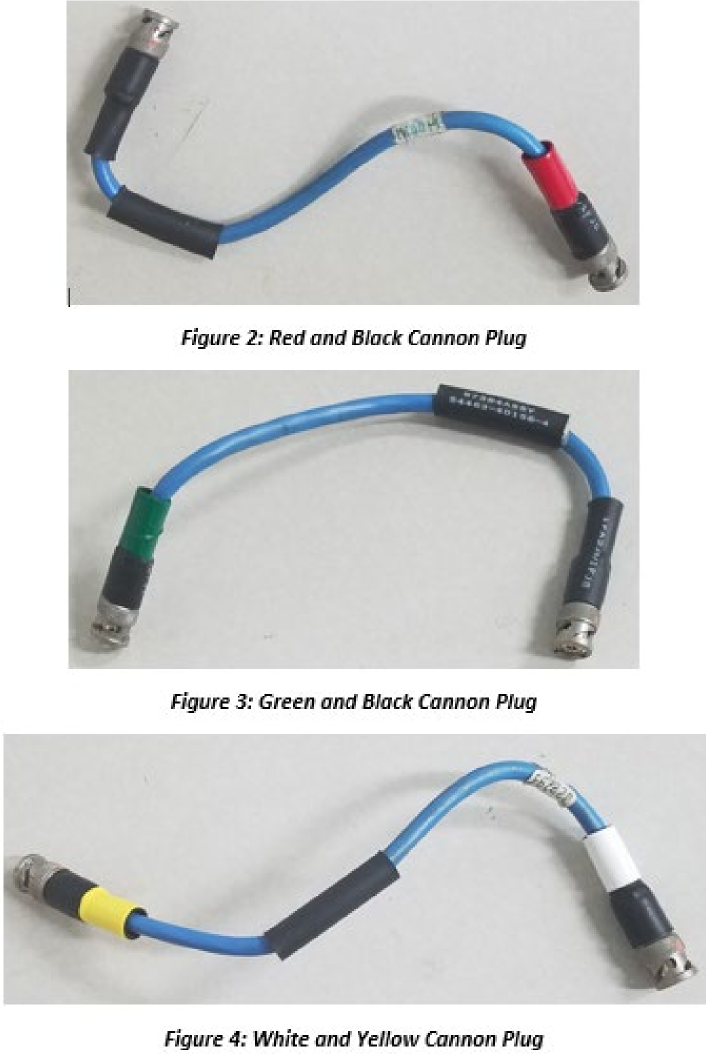


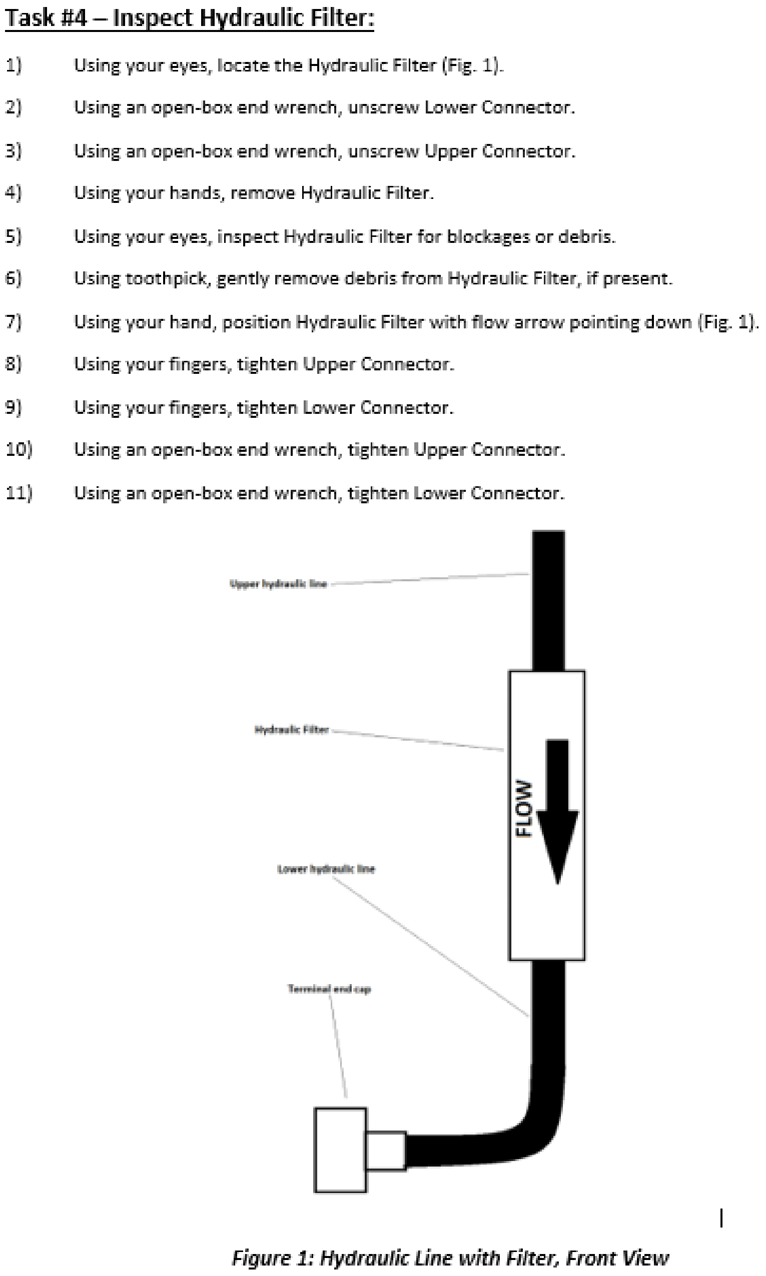
Figure 2: Red and Black Cannon Plug

Figure 3: Green and Black Cannon Plug

Figure 4: White and Yellow Cannon Plug

Figure 48. Task 3 Written Instructions, page 2

4. Task 4 (Inspection of Hydraulic Filter)



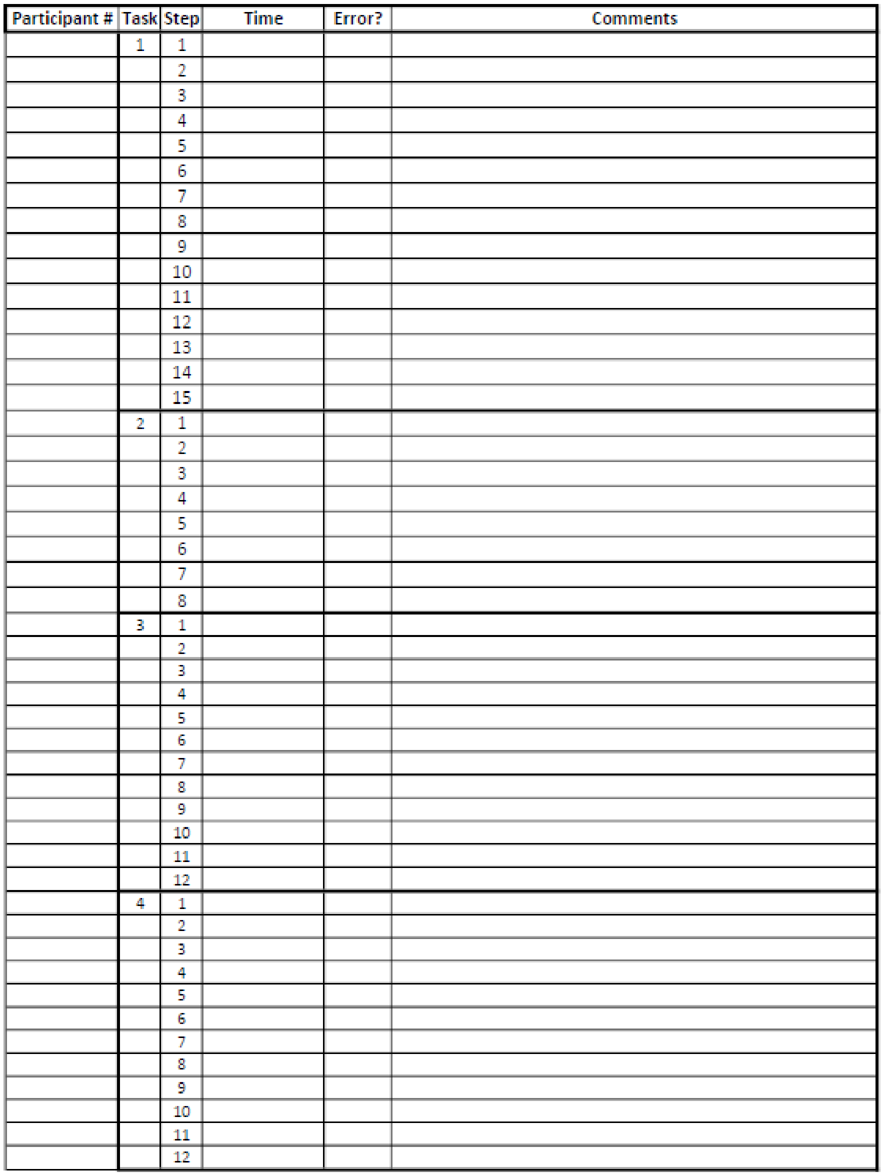
Task #4 – Inspect Hydraulic Filter:

1) Using your eyes, locate the Hydraulic Filter (Fig. 1).
2) Using an open-box end wrench, unscrew Lower Connector.
3) Using an open-box end wrench, unscrew Upper Connector.
4) Using your hands, remove Hydraulic Filter.
5) Using your eyes, inspect Hydraulic Filter for blockages or debris.
6) Using toothpick, gently remove debris from Hydraulic Filter, if present.
7) Using your hand, position Hydraulic Filter with flow arrow pointing down (Fig. 1).
8) Using your fingers, tighten Upper Connector.
9) Using your fingers, tighten Lower Connector.
10) Using an open-box end wrench, tighten Upper Connector.
11) Using an open-box end wrench, tighten Lower Connector.

Figure 1: Hydraulic Line with Filter, Front View

Figure 49. Task 4 Written Instructions

D. SCORING SHEET DURING TASK EXECUTION



Participant #	Task	Step	Time	Error?	Comments
	1	1			
		2			
		3			
		4			
		5			
		6			
		7			
		8			
		9			
		10			
		11			
		12			
		13			
		14			
		15			
	2	1			
		2			
		3			
		4			
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		6			
		7			
		8			
	3	1			
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		7			
		8			
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		11			
		12			
	4	1			
		2			
		3			
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		5			
		6			
		7			
		8			
		9			
		10			
		11			
		12			

Figure 50. Table Used To Score Participant Performance

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