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The Effectiveness of Augmented Reality for Astronauts on Lunar Missions: An Analog Study

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THE EFFECTIVENESS OF AUGMENTED REALITY FOR ASTRONAUTS ON LUNAR MISSIONS: AN ANALOG STUDY

By

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Abstract

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The uses of augmented reality and head-up displays are becoming more prominent in industries such as aviation, automotive, and medicine. An augmented reality device such as the Microsoft HoloLens can project holograms onto the user’s natural field of view to assist with completion of a variety of tasks. Unfortunately, only a little research and development has begun in the space sector for astronauts using these head-up displays. Future lunar missions could incorporate augmented reality for astronauts to ease task load and improve accuracy. This study evaluated the usability, subjective workload, and task performance of 22 participants using the Microsoft HoloLens to complete tasks that are analogous to those completed by astronauts on a lunar mission, including navigation, rock sample collection, and maintenance tasks. Results from the usability survey, NASA-TLX, and usability interview suggested that augmented reality could support astronaut missions by means of reduced workload and task errors. Usability data information collected from the participants sought to improve on the user interface and confirmed the aforementioned results. The researcher concluded that further research must be conducted to test the development of augmented reality interfaces along with the usability aspect by the National Aeronautics and Space Administration astronauts.

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Chapter I

Introduction

The advancement of technology has brought about a great change on how we view displays. For example, computer displays have evolved to something that can fit in our pockets in the form of mobile devices. This huge development has integrated the uses of Head-Up Displays (HUDs) and Augmented Reality in certain industries and are becoming more prominent (Vergara Villegas, Cruz Sánchez, Rodríguez Jorge, & Nandayapa Alfaro, 2016). Why are they being used? How are they helpful in the industry, and what are their advantages? The space industry, notably in relation to the International Space Station (ISS), is filled with highly complex tasks and procedures that require extensive knowledge and accuracy to be accomplished. The tasks that are performed by astronauts on-board the ISS, which range from operational to maintenance, are all performed in accordance with specific procedures. The complexity of these tasks calls for intensive training and well-developed operational data files to successfully complete tasks (Hoppenbrouwers et al., 2017). Historical and modern spacesuits are considered small spacecraft, which are used for extravehicular activities (EVAs). The controls and displays that are mounted on the spacesuit are relatively simplified as opposed to the ones on the actual spacecraft itself (Colford, 2002). However, there has been little research and development done in order to incorporate HUDs and AR into spacesuits for astronauts. Future missions will be aimed to explore larger parts of the lunar surface, thus paving the way for future planet exploration (Dunbar, 2019).

According to Scheuring et al. (2008), there was always a recurring issue during the lunar surface operations on the Apollo missions of a packed schedule. The astronauts wanted to reduce their workload and minimize lunar extravehicular activities (LEVAs) in order to minimize error and injury (Scheuring et al., 2008). The development and support of AR into spacesuits for lunar exploration will likely have a positive impact on the space industry (Ramsey, 2015). NASA astronaut Scott Kelly, in an interview, stated that he tried an AR device, i.e., Microsoft HoloLens. He added, “There are certain capabilities that would be good for us to use onboard the space station” (Franzen, 2015, para. 7). In a news article from NASA’s Jet Propulsion Laboratory (2015), Sam Scimemi, who is the director of the ISS program at NASA, stated that the HoloLens and other virtual and mixed reality devices could help drive future exploration (NASA, 2015). Therefore, the incorporation of AR will improve astronaut performance (Neumann & Majoros, 2002).

Significance of the Study

There has been limited research conducted using AR in the space industry to analyze its benefits on astronaut missions and tasks (Norris & Luo, 2016). Further, to the knowledge of the researcher, results from studies involving the HoloLens for the use of astronautics tasks have not yet been published, thereby leaving a considerable gap in the relevant body of knowledge. It has been suggested that the use of AR in the space industry will benefit astronauts by displaying procedural information thus reducing error and improving performance (Braly, Nuernberger, & Kim, 2019). Astronauts will encounter complex missions, such as setting up lunar outposts and thus eventually pave the way for settlement on Mars; it is thus essential for private companies and NASA to develop and advance current AR technology (Dunbar, 2019). Research on the development of AR will have a positive impact on the space industry (Ramsey, 2015).

This research study will serve as a springboard for revisiting the development and incorporation of AR into an astronaut’s spacesuit. Specifically, the research will focus on factors such as usability, degree of successful task completion trends in task-related errors, subjective workload incurred, and learnability of and acclimation to the software application developed. Results from the test could show the potential improvements in efficiency AR could have on astronauts performing tasks (Ramsey, 2015). Results could also indicate aspects of the AR interface that could benefit from future design improvements prior to supporting astronautics applications.

Statement of the Problem

The future of space exploration will involve preparing to send astronauts to the lunar surface for further exploration (Dunbar, 2019). Specifically, the Artemis lunar exploration program will use new technologies and systems to explore more of the lunar surface (Dunbar, 2019). This program, according to NASA, will “demonstrate new technologies, capabilities, and business approaches needed for future exploration including Mars (Dunbar, 2019, para. 2).” The goal during these missions, according to NASA, is to demonstrate and develop new technologies before sending astronauts to Mars, thus playing an important role in helping astronauts with their exploration tasks. Space is an extremely harsh environment, and the missions astronauts undergo consist of complex tasks. The workload and mental and physical demands astronauts encounter during these tasks are enormous (Manzey et al., 1995). Therefore, advancement in the technology in spacesuits will facilitate the necessary means for astronauts to go through their tasks smoothly with minimal errors. To help in reducing workload and improve task performance on space exploration missions, such as the lunar surface, the use of AR technology should be examined.

As stated by Colford (2002), the current equipment on the spacesuit which has been in use since 1983 (Mosher, 2019), consists of controls that are simplified to show the status or any malfunction of the suit and a small booklet of checklists and procedures to overcome potential problems during EVAs. The incorporation of AR to display this information to the astronauts will improve procedural work on tasks and reduced the potential for error and accidents (Braly, Nuernberger, & Kim, 2019). According to astronaut Scott Kelly, having procedures in the form of AR right in the field of view (FOV) would be helpful (Franzen, 2015). This would help with their task performance. A guided task using AR could help reduce the potential for errors. Scott Kelly has described how an expert on the ground can assist astronauts using AR by seeing what the astronauts are seeing and making annotations, pointing to relevant parts of the environment, and guiding them through a task (Franzen, 2015).

Purpose Statement

The purpose of this study was to collect qualitative and quantitative data on the usability of AR in terms of how it will help astronauts in the guidance of task performance during a lunar mission through the utilization of analog participants and tasks.

Research Questions

The following research questions were formulated for this study:

1. To what extent could AR support astronauts in their task completion during lunar missions?

2. What are some of the usability considerations involved in incorporating AR into astronauts’ tasks during lunar missions?
3. Does use of the Remote Assist function aid in task completion?
4. How learnable are the HoloLens functions across exposures to the hardware?

Hypotheses

The following hypotheses were formulated for this research:

1. The total number of errors committed using the AR UI in Mission 1 will exceed the number of errors using the AR UI in Mission 2.
2. The number of errors committed using the AR UI in completing the maintenance tasks in Mission 1 will exceed the number of errors committed using the AR UI in completing the maintenance tasks in Mission 2.
3. The number of errors committed using the AR UI in completing the rock sample collection tasks in Mission 1 will exceed the number of errors committed using the AR UI in completing the rock sample collection tasks in Mission 2.
4. The overall subjective workload in Mission 1 will exceed that of Mission 2.
5. Subjective mental demand in Mission 1 will exceed that of Mission 2.
6. Subjective physical demand in Mission 1 will exceed that of Mission 2.
7. Subjective temporal demand in Mission 1 will exceed that of Mission 2.
8. Subjective rating of performance in Mission 1 will be lower than that of Mission 2.
9. Subjective effort in Mission 1 will exceed that of Mission 2.
10. Subjective frustration in Mission 1 will exceed that of Mission 2.

11. Ratings of ease of using the HoloLens will be higher in Mission 2 than in Mission 1.
12. Ratings of pleasantness of using the AR UI will be higher in Mission 2 than in Mission 1.

Delimitations

The focus of this study was to analyze the use of the Microsoft Hololens as an AR device for astronauts in lunar environments. The data that was collected was not modified. Due to limited financial resources, the researcher reserved a multipurpose room at the Embry Riddle Aeronautical University (ERAU) Daytona Beach campus and configured it to replicate a lunar surface. Displays relevant to tasks replicating those that would likely be performed by astronauts on a lunar base were developed, and their relevant components were displayed on the Microsoft Hololens to simulate AR in space. A fuel-heat exchanger filter component from an aircraft was used to replicate a bacteria filter component that astronauts would likely use on a lunar base. Due to the lack of funding and accessibility, the researcher could not obtain actual components that were used aboard the ISS. In an effort to mitigate the effects of other factors (e.g., non-environmental) on experience, participants were required to meet a set of research standards: participants were selected from a pool of students who were currently enrolled in or had completed the Turbine Engines academic course (AS-311) at ERAU, Daytona Beach campus.

Due to the exploratory nature of this research topic, only 22 participants were used to generate the data. More participants would be beneficial to drawing conclusions based on the results. The ERAU Institutional Review Board (IRB) required the participants to be 18 years of age or older. The researcher set the requirement that the participant be currently enrolled or completed the aircraft turbine engines course. The requirement for this course increased the probability that participants would possess better knowledge on aircraft components, since the fuel heat exchanger component was used in the maintenance task. Furthermore, participants who experience any kind of motion sickness were excluded from participating.

The researcher chose not to simulate many aspects of the space environment (weightlessness, spacesuits, scientific experiments, etc.) due to limited financial resources and ERAU IRB requirements. The ERAU IRB also required that the Hololens be taken off immediately in case participants experience any discomfort.

Limitations and Assumptions

For the purpose of the research, participants were enclosed in a room with no communication with the outside world (with the exception of simulated mission control). The researcher assumed that the HoloLens or a similar AR device could and would be used in lunar missions. The researcher also assumed that the tasks that were created would replicate those that would be executed by astronauts on a lunar base, whereas no previous such missions have yet been executed in the real world. To meet the IRB requirements, the researcher felt that should any participant experience discomfort during the experiment, the research would be terminated immediately, and no data would be collected from the participant. An assumption was made that the selected participants had prior knowledge on the tasks that were to be performed due to the requirement of having completed the aircraft turbine engines course, and that they completed them to the best of their abilities in terms of speed and precision. The assumption was also made that the participants were isolated from the physical world with no ability to get external help during their simulated space mission. The researcher assumed that the characteristics of the population was similar in some ways to the astronaut population; the participants' background in flight training and technical training in engine components would represent some of the training requirements for astronauts. To meet the needs of the investigation, the researcher assumed the participants would follow the steps presented to them in the AR UI they were assigned and would willingly follow all procedures and cooperate with the scenarios.

Definitions of Terms

Astronaut	A person who works aboard a spacecraft (Astronauts, 2014).
Augmented Reality	A system which supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world (Azuma et al., 2001).
Effort	The level of difficulty to work to accomplish the level of performance (Hart & Staveland, 1988).
Frustration	Insecurities, discouragement, irritation, stress, and annoyance (Hart & Staveland, 1988).
HoloLens	A wearable head-mounted display in which users can see, hear, and interact with holograms that are displayed within an environment (Microsoft, 2019).
Lunar Outpost	A platform that will contain a power element, habitation, logistics, and airlock capabilities (Warner, 2018).

Mental Demand	The level of mental and perceptual activity (e.g. thinking, deciding, etc.) required to perform a task (Valdehita et al., 2004).
Performance	Successfulness in accomplishing task (Hart& Staveland, 1988).
Physical Demand	The level of physical activity (e.g. controlling, activating, etc.) required to perform a task (Valdehita et al., 2004).
Temporal Demand	Pressure due to time constraints during the task (Valdehita et al., 2004).
Usability	The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction (Interaction Design Foundation, 2019).
Workload	A measurement of mental demand, physical demand, temporal demand, performance, effort, and frustration derived from the NASA-TLX (Hart & Staveland, 1988).

List of Acronyms

AR	Augmented Reality
ERAU	Embry-Riddle Aeronautical University
EVA	Extravehicular Activities
FOV	Field of View
HUD	Heads-Up Display
IRB	Institutional Review Board

ISS	International Space Station
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
OS	Operating System
TLX	Task Load Index
UI	User Interface
VR	Virtual Reality

Chapter II

Review of the Relevant Literature

Missions that astronauts undertake are mentally and physically demanding. Due to the complexity of space missions, astronauts are required to be accurate in the tasks they perform. The tasks that are performed by astronauts from operations to maintenance of the station systems are high risk and are performed according to specific procedures (Hoppenbrouwers et al., 2017). The most recent research that NASA is currently undertaking is the use of the Hololens on the ISS. However, data based on certain factors such as usability, time to complete tasks, task errors, and workload have been unavailable, restricted, or under review (Norris & Luo, 2016). There have been some devices tested to provide an astronaut with a “hands-free” environment. Future missions to the moon will require an upgrade in the EVA suit (Mahoney, 2019). In the study by the Space Medicine Division at the NASA Johnson Space Center, the recommendations for future lunar missions were to incorporate a heads-up display (HUD) with consumable, biomedical, and navigation information on demand. They also concluded that using a HUD would increase operational efficiency (Scheuring et al., 2008).

Augmented Reality

Augmented reality (AR) is a system which supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world (Azuma et al., 2001). According to Azuma (1997), the definition of AR is something that requires the use of head-mounted displays. This is a reference to Sutherland’s work in the 1960s in which he used a see-through Head-Mounted display to present 3D graphics (Azuma et al., 2001). Azuma’s research focused on integrating 3D virtual objects into 3D real environment in real time (Azuma, 1997). Azuma et al. (2001) explains how he published a survey that defined the field of AR and described the problems and the developments until that point. The use of AR has greatly enhanced the user's perception and interaction with the real world (Azuma, 1997). With this enhancement, examples of the areas in which AR application has been explored are medicine, maintenance and repair, entertainment, etc. (Azuma, 1997).

Heads Up/Head-Worn/Head-Mounted Displays

In order to merge the virtual and real environments, there must be some sort of display that needs to be used for viewing by the user. These displays can be head worn, handheld, and projective (Azuma et al., 2001). For the purpose of this study, the research will focus on head worn displays. The device is mounted on the user's head and provides the image in front of their eyes (Azuma et al., 2001). Azuma et al. (2001) describes the device in which the display has an optical see-through method which provides the AR overlay through a transparent display. These head displays would be similar to wearing eyeglasses with the AR being displayed to the user. This ensures that the user can see the real world environment unlike virtual reality where the user is immersed in a virtually constructed world. An example of this would be the Microsoft HoloLens which is a self-contained, holographic computer enabling users to interact with holograms in the real world environment (Ramsey, 2015).

Usability Considerations of Augmented Reality

There have been extensive studies done on the usability of AR with a growing number of user-based experiments (Dey, Billinghurst, Lindeman, & Swan II, 2018). The journal *Frontiers in Robotics and AI* published a review of AR usability studies from

2005 to 2014 which included AR usability in education, entertainment and gaming, industrial, medical, navigation and driving, and tourism and exploration. There remains continuous testing that needs to be done, and user experience issues still need to be improved in order for the technology to be widely accepted by end users (Dey, Billinghurst, Lindeman, & Swan II, 2018). The analysis done provided a wide range of usability results from qualitative and quantitative data. In the industrial studies conducted, focus was generally based on manufacturing / assembly related tasks. The quantitative data collected were completion times, task localization time, head movement, and errors. Qualitative data focused on questionnaire to get an indication of user experience. Another example is in the medical industry. These AR applications were designed for highly trained medical practitioners. The data gathered were all quantitative which focused on user performance and alignment accuracy. The most popular method of usability data collected were in the form of questionnaire to get user feedback (Dey, Billinghurst, Lindeman, & Swan II, 2018).

AR can also help the human cognitive processes. Neumann & Majoros (2002) highlights the potential benefits users of AR have. These can include information access, reduced likelihood of error, enhanced motivation, and concurrent training and performance. The research paper explains each of the users' benefits in detail. In relation to manufacturing industries, a study was conducted to show that AR has many benefits and is used to increase efficiency and performance of workers (Tang, Owen, Biocca, & Mou, 2003). AR can reduce head and eye movement as it displays all the information in front of the user, it reduces attention switching, meaning that the users are focused on a task and don't have to divert their attention to another screen, lastly it supports spatial cognition and mental transformation. This helps the user to memorize information more effectively due to the relation of information to physical objects and locations in the real world (Tang, Owen, Biocca, & Mou, 2003). A study by Tatić & Tešić (2017) created an AR system that would guide workers though various work and safety procedures in the form of an interactive checklist. Their results showed the technology could be used to decrease the error rate. It also showed that interaction with the database through checklists ensured that all the steps were performed in correct order.

AR has the potential to reduce mental workload on the user. Mental workload is a measurement of the mental strain that results from a particular task (Wickens et al., 1998). Hoover (2018) states, "one way in which AR instructions can reduce mental workload is by providing sequential task instructions, rather than using paper manuals." In a study done by De Crescenzio et al. (2011), the authors demonstrated AR on oil checks on an aircraft. They showed that the technology improved task efficiency. They also measured workload by applying the NASA-TLX (Task Load Index) form. The results showed that the mental, physical, and temporal workload were low. A study done by Braly, Nuernberger, and Kim (2019) showed the use of AR for procedural work on an ISS science instrument. The participants were tasked to search for a named cable and connect/disconnect the cable from a port using a paper instruction method and an AR instruction method. The results from the NASA-TLX showed that the mental workload was significantly lower for the AR instruction method. This shows that AR can also reduce mental load on the user.

There are also limitations that have been identified by researchers with AR technology. Khor et al. (2016) identifies some of the limitations of AR in the surgical environment. They state that AR systems will require “increasingly powerful microcomputers to drive AR.” Another major limitation pointed out is that the device has to be light, mobile, comfortable, and functional for extended periods of time (Khor et al., 2016). In a technical report by Krevelen, a section focuses on the limitations of AR. Some of the limitations mentioned are contrast, high resolution, and FOV (Krevelen, 2007). He also mentions that issues regarding interfaces, costs, weight, power usage, and ergonomics must be addressed. However, the technology has yet to progress, be further developed, and will improve with time (Khor et al., 2016).

Integration of Augmented Reality into the Industry

AR is being explored more and more in industries that perform complex tasks. Azuma states that there are at least six classes of AR applications that have been explored, some of them being medical visualization, maintenance and repair, annotation, robot path planning, entertainment, and military aircraft navigation and targeting (Azuma, 1997). In the medical industry, the use of digital video-assisted surgery techniques are required in the operating room (Bosc et al., 2018). However, this makes it impossible for the surgeon to have a heads-up and hands-free view while operating, which basically means the surgeon’s eyes and hands cannot be diverted from the operating field (Bosc et al., 2018). Therefore, the incorporation of AR for the surgeon would be highly effective for the surgeon. In the area of manufacturing and repair, prototype projects have been demonstrated. Feiner (1993) developed a laser printer maintenance application that shows the user a computer-generated wireframe explaining to the user how to remove the paper tray. Another example is from Boeing where AR technology is being used to guide a technician in building a wiring harness for the airplane's electrical system (Azuma, 1997).

Microsoft HoloLens

The Microsoft HoloLens is a wearable head mounted display running the Windows Mixed Reality platform under the Windows 10 operating system (OS), which was manufactured and developed by Microsoft (Microsoft, 2019). Users of this device can see, hear, and interact with holograms that are displayed within an environment (Microsoft, 2019). The holograms are displayed through semitransparent holographic lenses which generate multidimensional full-color holograms (Roberts, 2016). The HoloLens is different from virtual reality (VR) headsets such as HTC Vive, Oculus Rift, etc. VR headsets immerse the user into a fully simulated environment, whereas the Hololens uses the real world as its canvas to overlay virtual elements (Roberts, 2016). There are a few limitations with the device such as its FOV and tinted visor. The HoloLens' FOV is 34 degrees diagonally, whereas the HoloLens 2 is 52 degrees diagonally (Goode, 2019). This is limiting as holograms can get cut off beyond the FOV range. The holographic lenses are housed behind a tinted visor (Microsoft, 2019). This tint can cause slight color disruptions while looking at real world objects

Microsoft HoloLens in industrial settings. There have been a few industries that have incorporated the Microsoft Hololens into their line of work. A few of these industries are: Case Western Reserve University, Boeing, and Tyssenkrupp (an industrial engineering and steel production company).

In the education industry, Case Western Reserve University uses the Hololens to transform learning by giving students three-dimensional images to learn anatomy. In a demonstration, students were shown a hologram of the digestive system with labels on specific organs. Another example was based on a hologram of a holographic heart. A student was able to examine the holographic heart. A professor from this institution stated, “With the HoloLens, you see it truly in 3D. You can take parts in and out. You can turn it around. You can see the blood pumping-the entire system.” (Lubinger & Hammer, 2015).

In the engineering industry, Boeing and Tyssenkrupp have both incorporated the HoloLens in development and servicing equipment. Boeing is using the Hololens to manufacture the Starliner transport module for the ISS. An example of its use is to see if there is clearance and space for a human to get access to onboard components that might need fixing. They have also been using it for training staff in manufacturing and servicing equipment. They have included test guidance for the individual learning tasks, as well as voice-over guidance to guide engineers through the process (MacPhedran, 2018). Tyssenkrupp has begun using the Hololens in the elevator industry for use in remote support, training, and preparation for the job. Remote support prevents the need to fly in an engineer to locations. Instead, technicians can connect with engineers over Skype and get real time information on repairs. In training, the HoloLens lets the trainees see parts in 3D to help understand and self-learn. Finally, the Hololens provides a hands free environment (Roberts, 2016).

NASA’s astronauts. The definition of the word astronaut is a person who is trained to operate or work aboard a spacecraft (NASA, n.d). According to NASA’s Astronaut Selection and Training (n.d), in order to qualify as a United States astronaut, applicants must possess a bachelor’s degree from an accredited institution in engineering, biological science, physical science, or mathematics. After obtaining the required degree candidates must possess three years of related, professional experience or at least 1,000 hours of pilot-in-command time in jet aircraft. Lastly, candidates must possess the ability to pass the NASA long-duration space flight physical. The flight physical requires candidates' distant and near visual acuity to be correctable to 20/20 in each eye, blood pressure not to exceed 140/90 measured in a sitting position, and a standing height between 62 and 75 inches (NASA, n.d).

Spacesuit systems. A spacesuit is considered to be a very small spacecraft. Astronauts use these suits to perform EVAs to service and maintain the ISS. Colford (2002) describes the equipment on an American spacesuit. He states that the controls on the suits are simplified, they work automatically, and inform the astronauts if there is a malfunction with the suit. These suits have display boxes mounted on the chest portion on the outside of the suit. Some of the controls that are located on these boxes cannot be seen directly from the inside of the astronaut helmet, but they must be viewed from a mirror that is worn on the astronaut's wrists. Some of the controls include communication systems audio levels, an oxygen supply actuator, and a valve controlling temperature regulation.

The wrist region of the suits accommodates two other information displays. One display is a small booklet of checklists and procedures to overcome potential problems during EVAs. It can also be used to make notes on specific objectives. The other display that is part of the suit is a manual-wind, 12-hour-movement mechanical chronometer wristwatch that is still being used since the Apollo missions (Colford, 2002).

NASA recently introduced a new spacesuit for their future lunar missions. The suit will allow astronauts to accomplish much more complex tasks due to technological advances (Mahoney, 2019). According to NASA's article on the next generation spacesuits, it can tolerate greater temperatures, with an improvement in the Portable Life Support System. There have also been improvements in mobility and communications. The future lunar missions will demonstrate and develop new technologies and capabilities before sending astronauts on missions to Mars (Dunbar, 2019). Therefore, this brings about improvement in current technology used on spacesuits which will help in enhancing astronaut performance.

International Space Station. The International Space Station (ISS) is a large spacecraft that is in orbit around the Earth. It is a unique science laboratory which several nations worked together to build. The ISS is as large as a football field and was assembled by astronauts in space. It houses multiple laboratories from the United States, Russia, Japan, and Europe (Dunbar, 2015). The maintenance operations related to the ISS are complex and take into account aspects such as the configuration of the elements, operational capabilities, the timeline of maintenance task, and the tools and support equipment (Angelini & Costa, 2002). The crews are not all trained on all possible equipment failures that can occur among the different elements with the related corrective maintenance actions (Angelini & Costa, 2002). Therefore, they would require the ISS maintenance manuals to complete the tasks successfully.

Apollo missions and astronaut rock sample collection. The Apollo program was a NASA program that resulted in American astronauts making a total of 11 spaceflights and being the first to walk on the moon. During these missions, the astronauts conducted scientific research, studied the lunar surface, and collected moon rocks to bring back to Earth (Loff, 2015). Apollo 11 began the gathering of lunar surface samples. The astronauts gathered and verbally reported the lunar rock samples they were collecting. The Apollo 12 mission began an extensive series of lunar exploration tasks, including lunar inspection, surveys, and samplings in landing areas (Loff, 2015). Apollo 14 set the stage for lunar geology investigations and collecting of surface material samples for return to Earth. These tasks carried on Apollo 15 and Apollo 16. In conclusion to the Apollo program, the Apollo 17 mission included geological surveying and sampling of materials with the help of the first astronaut-scientist (Loff, 2015).

Lunar rock sample collection was accomplished with special tools designed for the astronauts. Tongs were used to pick up the samples: scoops to collect soil samples and rakes to collect small pebbles. The astronauts followed a specific procedure for collecting samples. Prior to the samples being collected, they were photographed, which would assist in interpreting their history. There was careful planning of sample collection prior to the start of every mission. The astronauts referenced their checklist on their right arm to guide them while performing these tasks. The astronauts were also provided with advice during their EVAs from a team of geologists who were present at mission control (USRA, 2019).

ISS tasks. The ISS is the largest and most complex spacecraft built so far (Colford, 2002). It is composed of different modules and systems that have specific manuals dedicated to them. Hoppenbrouwers et al. (2017) state that the tasks that are performed by astronauts from operations and maintenance of the station systems are high risk and are performed according to procedures. The ISS has a “user manual” called

Operation Data Files (ODF) which contains a significant amount of information (Hoppenbrouwers et al., 2017). The documents present in the guide contain the operations of the ISS, EVA Operations, Cargo Vehicle Procedures, Malfunctions, and Emergency Operations, etc (SpaceRef Interactive Inc., n.d.). It can have multiple faces which go from traditional step-by-step procedures, scripts, cue cards, over displays, to software which helps in guiding the crew through tasks (Hoppenbrouwers, Ferra, Markus, & Wolff, 2017). The crew on-board the ISS view these procedures using the International Procedure Viewer (IPV). The IPV is a browser-based viewer and are viewed on the onboard Station Support Computers (SSC) which are basically laptops connected to either Wi-Fi or Ethernet. They can also be viewed on tablets which makes it easier to move around to any site in the station. These checklists, tasks, and graphical images can be displayed using AR for easy access to the astronaut.

Astronaut workload. Astronauts work in the space environment which is described as one of the most extreme environments for humans. There is a demand for complex processes of psychological and physiological adaptations that astronauts need to get accustomed to (Manzey & Lorenz, 1999). Astronaut tasks in a spacecraft or onboard a space station include the maintenance of technical systems as well as conducting different experiments. These experiments usually are often associated with high mental and physical workload and time pressure (Manzey & Lorenz, 1999). Neumann and Majoros (2002) state that using AR will reduce the potential for error and improve training and performance. This will aid in reducing the workload faced by the astronauts.

Future lunar missions. Ever since the Apollo missions, the moon has remained a great interest to NASA and scientists around the world (Dunbar, 2019). According to

NASA, the Artemis lunar exploration program will allow astronauts to explore more parts of the lunar surface. This exploration will set the stage and provide proving ground to test technologies and the resources to take humans to Mars, which will include building sustainable, reusable architecture (Dunbar, 2019). The new missions will entail deeper exploration among the rare and most precious commodities in space, which will offer potential sustenance and fuel for future explorers (NASA, 2018). NASA aims to develop a platform that will validate new technologies and systems as they build infrastructures to support missions to the surface of the moon which will help pave the way to Mars (NASA, 2018). This process includes studying requirements for the next-generation spacesuits needed for lunar exploration (NASA, 2018). The development and support of AR into spacesuits for lunar exploration is anticipated to have a positive impact on the space industry (Ramsey, 2015).

NASA and the Microsoft HoloLens. There is currently some research and development underway with Microsoft HoloLens and the National Aeronautics and Space Administration (NASA). According to NASA press release, NASA and Microsoft are testing the Microsoft HoloLens to provide virtual aid to the astronauts in Project Sidekick (2015). The main goals of this project will be reduction in crew training requirements and the increase of efficiency of working in space. The device will use Skype to allow a ground operator to see what a crew member sees and provide guidance during tasks (Ramsey, 2015).

According to NASA, Sidekick: Investigating Immersive Visualization Capabilities is a hands-free, wearable, remote assistance system that enables high-definition 3-D holograms mixed with real-time views, enabling new ways to communicate and work for astronauts in space (Norris & Luo, 2016). It is a collaboration between NASA and Microsoft to develop a project using the HoloLens for astronauts to use aboard the ISS (2015). The device has two modes of operation: a "Remote Expert Mode" and a "Standalone Mode." The remote expert mode uses Skype which allows a ground operator to see what the crew sees and provide them real-time guidance through a task. The standalone mode displays animated holographic procedures above the objects the crew is interacting with (Norris & Luo, 2016).

Before sending the HoloLens to the space station, NASA experimented with it at the Aquarius underwater research station in Key Largo, Florida. Here, astronauts used the device for tasks such as checking emergency breathing equipment. This was done by going through a series of steps which involved turning valves, finding and plugging in equipment, and setting up equipment to support an undersea robot (Metz, 2015). Jeff Norris, the project manager for NASAs HoloLens, and his team are working on applications for the HoloLens. For example, they are using AR for inventory management. This application will be able to recognize an object and show the user a path to where the object should be stored (Metz, 2015). Norris also states, "there are enormous challenges with building AR applications, the biggest being how the menu should look and how the user should interact with it when it's not shown on a laptop or a smartphone screen" (Metz, 2015).

The device was launched to the ISS in September 2015, and was received positively by the astronauts aboard. In an interview with astronaut Scott Kelly, he stated that he got to try it out and confirmed that there are certain capabilities that would be good to use onboard the ISS (Franzen, 2015). There were two uses he mentioned in the interview, the first use is having a procedure list right in the FOV which could be manipulated using voice commands, and scrolling though different steps. The second use would be having a ground expert guide the astronauts through tasks by seeing what they were and making annotations and pointing things out (Franzen, 2015). According to NASA's space station research database, the project ended in March 2016, with data being unavailable, restricted, or under review (Norris & Luo, 2016).

A few research studies have been conducted on Earth using AR for astronauts. In 2002, researchers at Massachusetts Institute of Technology (MIT) developed a HUD called WearSAT. This device provides text, graphics, and video to astronauts via a near-eye display. This acts as a client on a wireless network and had the potential to enhance work performance on astronauts during EVAs (Carr, Schwartz, & Rosenberg, 2002). However, this device is not considered to be an AR as it constricts the astronaut's view.

Another device called the Mobile procedure viewer (mobiPV) for the ISS is a wearable device which gives the astronauts a hands-free operational environment. This device provides them with a direct two-way link with ground control, and the system provides the ground with an exact view of the procedure being executed. This eventually evolved and led to the testing of the Microsoft HoloLens to perform similar functions (Hoppenbrouwers et al., 2017).

Summary

There has been a constant development in technology in the space industry ever since astronauts first exited the Earth's atmosphere. The ISS is a great example of all the advancement in technology that has come about, one being using AR for astronaut tasks. Microsoft's HoloLens was used by the astronauts on the ISS to conduct a maintenance task using holograms and remote assistance by mission control on the Earth. Future missions will require the lunar surface to be a testing ground for outposts to test new technologies which will eventually pave the way to Mars.

AR is a system which supplements the real world with virtual computer generated objects, i.e. holograms. AR systems are available in a variety of formats which range from something as small as a cellular phone to complex head mounted displays. AR has shown to enhance user's perception and interaction with the real world. There have been a number of fields such as medicine, maintenance, etc. where AR has been used successfully.

Head worn AR displays project the images in front of their eyes. This optical see-through method provides the AR overlay upon the user's natural FOV through a transparent display. This arrangement ensures the users are hands-free and can see the real world, unlike VR. In the industry, AR has helped in the development and servicing of equipment in companies such as Boeing (2018) and NASA.

The research done in terms of AR for astronauts has been limited. MIT developed a HUD device which is only capable of showing text, limited graphics, and videos to astronauts via a near-eye display. Additional ongoing research is the project set up by NASA and Microsoft to provide astronauts aboard the ISS with a hands free wearable remote assistance system to work in space called Project Sidekick: Investigating Immersive Visualization Capabilities; however, no related data has been published.

The future missions to space, as stated by NASA, will require astronauts to explore larger parts of the moon and setting up lunar bases which will require highly advanced technology. This new exploration will require upgrading and advancing spacesuits and astronaut equipment. The development and incorporation of AR in spacesuits for astronaut tasks will be a significant advancement and will change the ways astronauts work in space.

Chapter III

Methodology

Research Approach

The purpose of this research was to determine if using AR is advantageous for astronauts on missions, specifically those involving navigating the lunar surface on foot. In order to fulfill the research objective, the participants were tested using an AR device called the Microsoft HoloLens. In this mixed methods approach, the participants performed specific tasks with the HoloLens guiding them; both task performance and subjective outcomes were measured. This study was considered to be an exploratory study which was designed to assess the degree to which participants acclimated to the use of the AR device.

Design and Procedures

The researcher's initial idea for the project, before eventually being replaced with the current experimental design involving the Microsoft HoloLens, began with researching preexisting AR-HUD displays with the intention of configuring them to accommodate the needs of astronauts. However, the configuration of these devices was limited to its proprietary content. For example, the researcher could not make changes to the existing software to customize the display. The researcher then used an inexpensive credit card-sized computer called a Raspberry Pi to serve as the platform to deliver the holographic displays to the participants. This platform would be the beta test device to develop a structure to display to the astronauts. The Raspberry Pi is a small single-board computer that plugs into a display, a keyboard, and a mouse. The idea behind the Raspberry Pi is for new users to learn coding and to develop small electronic projects

(Raspberry Pi, n.d). It runs a specific OS called Raspbian, which is highly recommended and specifically designed for it. The OS performs the same basic functions as any other OS, such as making spreadsheets, word processing, browsing the internet, etc. The researcher developed a checklist that would be used by the participants which contained all the information to complete a task. This checklist was developed using a simple spreadsheet. Further development would have involved incorporation of the fitness tracker that would display its information to the astronaut.

In the original experimental plan, a teleprompter mirror would provide the basis to simulate a HUD. The glass teleprompter mirror which is known as a beam splitter mirror is semi-transparent (Two Way Mirrors, 2019). The mirror is transparent and has an anti-reflective coating that prevents double images. It was mounted on the 2.8-inch display screen at an angle to reflect the image from the display. In order to incorporate the HUD on an astronaut suit, a mock astronaut helmet was purchased from eBay. The helmet was designed to resemble the ones used in the Apollo missions. The helmet was comprised of interior padding and a plastic visor that could be opened and closed. The helmet was modified by the researcher to have a moveable mount. This movable mount held a 2.8-inch display which was connected to the Raspberry Pi to display the information to the astronauts. In order to control the OS on the display, a mini QWERTY keyboard with a mouse track-pad was used. This would then be attached on the astronaut’s arm. This display was then reflected by the mirror to the astronauts wearing the helmet. The Raspberry Pi and the 2.8-inch display are powered by a portable power bank that was attached to the hip of the astronaut.

The Microsoft HoloLens is a device that combined components such as a Windows OS, projectors, and lenses that displayed information in the form of holograms to the user. It provided greater capabilities than the Raspberry Pi, some of which include gesture control, user-centered interface, its own power source, a Windows OS, application design, and, most importantly, projecting holograms and information to the wearer of the device. Since NASA had begun testing the use of the HoloLens on the ISS (NASA, 2015), the researcher viewed it as advantageous to continue the testing and development of this platform to help support its use by astronauts.

Tools for development. In order to develop applications for the HoloLens, specific systems and programs were required (Microsoft, 2019). The Microsoft Mixed Reality website provided all the documentation and the checklist for getting started with HoloLens development. Some of the specific checklist items are installing the tools, tutorials and sample applications, unity development, etc.

Windows 10 OS. The most recent version of Windows OS needed to be installed on the PC to build mixed reality applications. Developer mode also needed to be enabled on the PC (Microsoft, 2019). In order to develop applications for Windows-based software, a program called Visual Studio was used to write code, debug, test, and deploy applications to the HoloLens. It compiles all the code from Unity for deployment to the HoloLens (Microsoft, 2019).

Unity. Unity is a cross-platform game engine program that is used to create 3D, 2D, virtual reality, and augmented reality applications. It is used in the development of games; automotive, transportation, and manufacturing; film, animations, and cinematics; and architecture, engineering, and construction (Unity Technologies, 2019). It helps in setting up computer code, UIs, animations etc. for building mixed reality applications. The version used by the researcher was Unity 2017.4.23f1 (64-bit). Using Mixed Reality Toolkit was the most efficient way to get started with development as it provided all the preset tools such as the camera, gestures, and cursor (Appendix E).

Mixed Reality Toolkit. The Mixed Reality Toolkit is an open source development kit for mixed reality applications (Microsoft, 2019). It helps in accelerating the development of applications for the HoloLens by providing all the basic framework and code that are required to initially set it up. Having these assets imported into Unity sets up projects automatically and provides the basic features of the HoloLens. These features and codes include setting up the mixed reality camera, the hand gestures, and voice controls.

Mixed reality camera. The HoloLens is designed to become the center of the wearer's holographic world (Microsoft, 2019). The real world appears behind the holograms the mixed reality camera displays. The camera component in Unity automatically renders the real world and will follow the user's head movement and rotation. In the development of the application, the UI, holograms, and animations are placed in front of the camera, which then can be viewed by the users. With the MRTK, the project is automatically configured, such as camera position to the origin, adding the input manager, and the default cursor. This arrangement sets up the HoloLens for the developer to customize its interface, add holograms, etc.

Gaze. Gaze is the primary method for the users to target holograms. It works by projecting a ray from the user's head where the headset is to the object (Microsoft, 2018). Gaze is then combined with the animated cursor to select objects. It is called *head gaze* as it is based on the direction in which the wearer's head is oriented. For this study, gaze helped the user to trigger animations on the mechanical component, select tasks on the checklist hologram, and navigate to the remote assistance application.

Animated cursor. The animated cursor works similar to a mouse pointer. It provides feedback for the user to realize where the headsets focus is. It allows the user to see their targeting point and provides feedback as to indicate what area or hologram will respond to their input (Microsoft, 2019). The user moves the cursor using gaze, sets the cursor on the object to be selected, and then uses the air tap gesture to activate it. The animated cursor contains two states – the *observe* state and the *interact* state. The *observe* state is where the user uses gaze to target a hologram, and the *interact* state is where the user uses the air tap gesture to interact with it.

Gesture (air tap). The air tap feature recognizes the hand movements and tracks hand gestures (Microsoft, 2018). Air tap works in combination with the gaze and the animated cursor. To activate it, the user initiates the *ready* gesture placing their hand with the index finger pointing up, in the HoloLens FOV. The user then 'air taps' to select the object. Placing the hand in the ready gesture changes the animated cursor into the interact state. The position of the hand is recognized by the forward-facing cameras on the HoloLens. For this study, the participant used the air tap gesture to activate tasks on the checklist hologram and to scroll through different menus.

Voice input. The voice input feature allows the user to use verbal commands to interact with objects. Specific string commands are programmed in Unity and then recognized by the application through the microphone on the HoloLens (Microsoft, 2018). In this study, the users could hide and show the checklist that gave them instructions on tasks. The commands that were set in Unity were ‘hide task’ to disable the checklist, and ‘show task’ to enable it.

Canvas. The canvas object provides the framework for the UI. It sets a blank screen in which text boxes can be drawn, buttons can be incorporated to recognize gestures, and animations can be triggered. For this study, a custom UI was developed with text that would guide participants through tasks. It was incorporated with buttons that scrolled through different menus, such as ‘start mission’, ‘next task’, ‘back,’ etc. It would also trigger the different animations that were used on the maintenance task.

Maintenance animations. Animations were created in Unity to closely resemble the real world objects. The animations were overlaid on the mechanical component, and with the help of printed pictures, the HoloLens camera would trigger the animations and guided the user to conduct the maintenance task. For example, if a bolt needed to be unfastened, an unfastening bolt animation would play (Figure 1). The animations that were created involved interactions with the power-cell component, bolts that needed to be fastened, the filter casing, and filters that needed to be replaced. The animations were cycled by the buttons in the canvas task checklist. The user would air tap the ‘task complete’ button to initiate the next animation. In order to display the animations, the user would point the HoloLens’ forward-facing camera at the printed image, in this case an oxygen tank, and the HoloLens would then start the animations automatically.

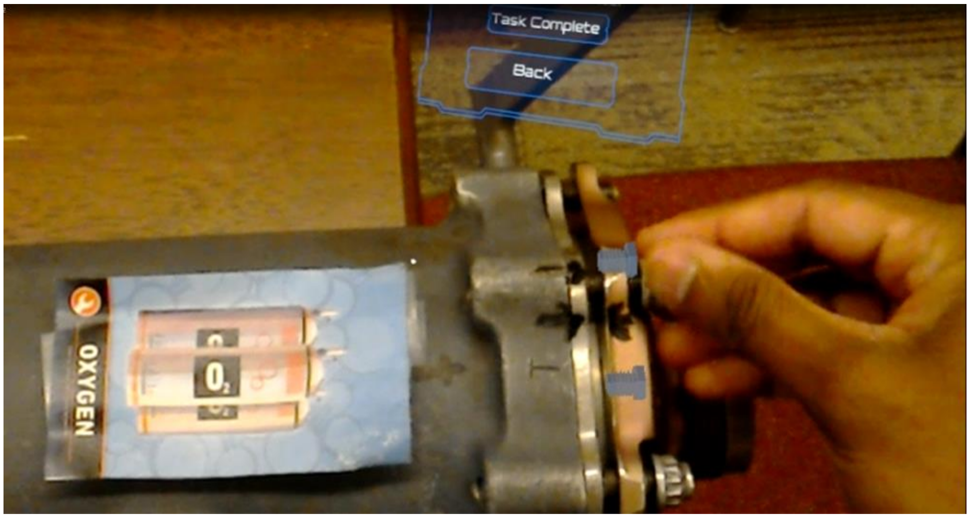
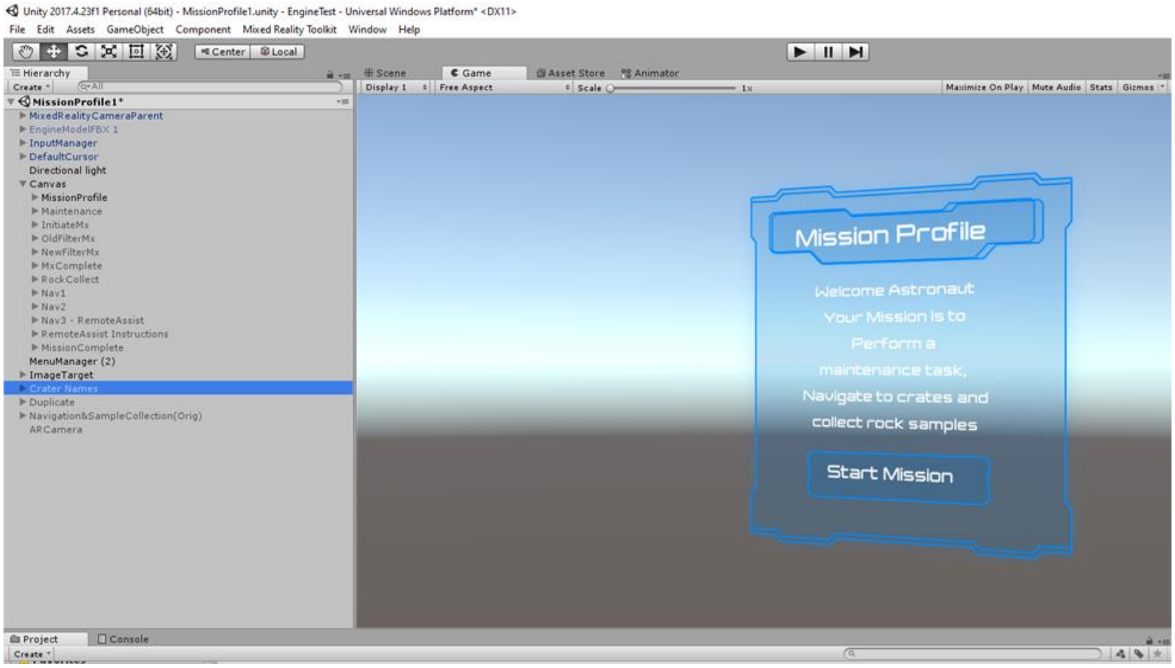


Figure 1. Maintenance animation.

Vuforia configuration. The Vuforia engine allows the HoloLens to connect AR experiences to specific images and objects in the environment (Vuforia, 2018). This functionality can be used to overlay step-by-step instructions in the form of holograms on top of physical objects. Specifically, when the AR camera on the HoloLens recognizes the target, in this case the printed image, the holograms and animations would initiate, and, using the functions of the UI, would trigger different animations. The animations would only appear when the user was gazing at the specific image.

World holograms. Unity can be used to create holograms for the HoloLens to display in the real world (Figure 2). These holograms work as if they were real objects and respond to gaze, gestures, and voice commands (Microsoft, 2018). The holograms used in this study were textual holograms for crater names, the canvas which included a text box with task lists, and animation holograms for the maintenance tasks.



Welcome Astronaut
Your Mission is to
Perform a
maintenance task,
Navigate to crates and
collect rock samples

Figure 2. Unity hologram setup.

AR UI. The AR UI was developed by the researcher. It provided the participant with mission tasks. The AR UI was in the form of a hologram that was to the right quadrant of the participants view. The UI was slightly angled and followed the participants' head orientation. It was in a fixed state, and the participant could not move or place the box where they wanted. There were buttons incorporated into the checklist such as start task, task complete, back, next mission, etc. The participants used the air tap gesture to manipulate these buttons

Dynamics 365 Remote Assist. The Remote Assist application provides the HoloLens user with heads-up, hands-free video calling. The user can collaborate with remote experts on a PC or mobile device to troubleshoot issues (Microsoft, 2019). The application also provides mixed reality annotations so that the wearer and a remotely located individual can interact and collaborate to complete tasks together (Microsoft, 2019). The user of the HoloLens can hear the person they have called through the HoloLens speakers located just above their ears. The ‘Collaborate and Annotate’ feature additionally provided the remote expert with the ability to ‘Draw in Space’ by selecting the ‘Ink’ tool and drawing annotations that would overlay upon the wearer’s FOV in order to highlight objects of interest. These annotations could then direct the wearer’s attention to specific aspects of their visual environment and then execute the necessary actions accordingly. In this study, the participant used Remote Assist to call an individual playing the role of a subject matter expert and share what they were seeing from their point of view as captured by the camera on the HoloLens. Specifically, the participant initiated a call to ‘mission control’ for assistance on the final rock sample collection task. Once the participants initiated the call, the researcher directed them on where to look and highlighted the rock sample to collect by circling the sample as it appeared upon the participant’s FOV (Figure 3).

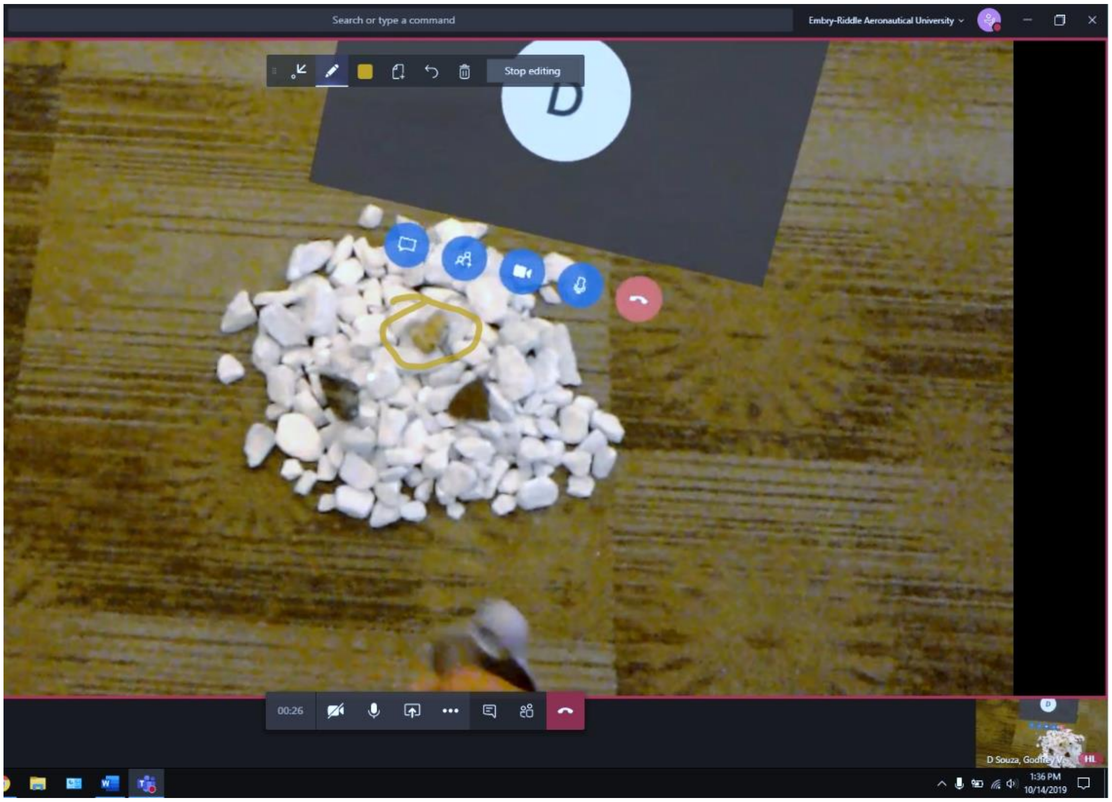


Figure 3. Remote Assist function.

Deploying and testing the application. After saving the scenes in Unity, the next step was to build the application on the Universal Windows Platform which compiles the code to be deployed in Microsoft Visual Studio. Once the application had been constructed in Visual Studio, the next step was to pair the HoloLens with the program using its I.P address. Finally, the application was built using Visual Studio and deployed to the HoloLens.

Mission control. An external console was set up near the simulated lunar surface and was manned by the researcher. The purpose of mission control was to record data from each participant such as task times, task completion, and any errors or difficulties the participant encountered. Another task of mission control was to provide guidance for the rock sample collection during the remote assistance portion of this session. Once the call was initiated by the participant via Remote Assist, the researcher could see the crater they were looking at and was able to provide visual guidance on which rock sample to collect.

HoloLens familiarization training. The participants underwent two different training sessions to work the device and make use of all its functions. The first training session was the HoloLens training, which was developed by Microsoft and comes installed with the device. The second training session was the mission training application, which was developed by the researcher and contained training objectives and content specific to the missions in the study.

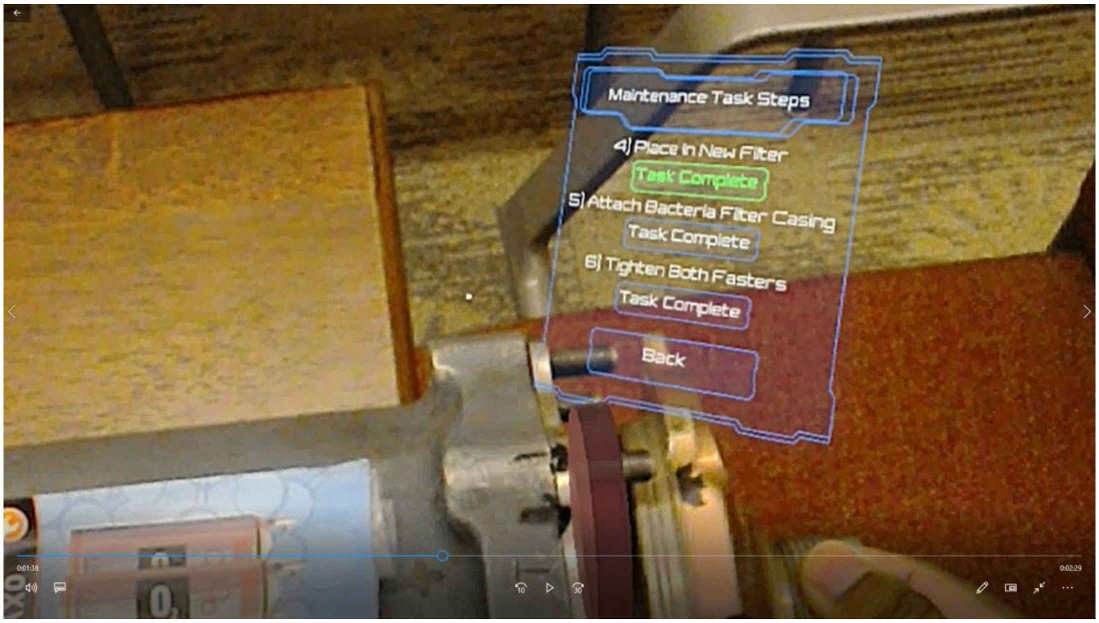
Pre-study briefing. The participants were briefed according to the checklist (see Appendix H). The briefing included the explanation of the room setup in which the study was conducted and a brief overview of the tasks involved. The participants were briefed that the crater names and lunar base would show up as holograms when they wore the HoloLens. The mechanical component was explained as having two parts: a filter replacement and a power-cell insertion. The HoloLens was introduced to the participant with its background and components. Following the briefing, the training on how to use the device took place.

HoloLens training application. In order to take full advantage of the HoloLens, as the Mission Profile made use of all its different functions, the participant had to become familiarized with all its functions. The HoloLens comes with a built-in training application which goes through its different functions such as, gaze, hand gestures, voice commands, etc. The training session is guided by a voice activated A.I. In this training, the participants practice the gestures along with the training program's guidance. The program would only advance to the next gesture training if the participant performed the previous correctly. The participant could perform the training application as many times as they needed until they felt comfortable and familiarized with the device.

The training started off with the adjustment of the headset so that the participant could see all four corners of the hologram box. Once the headset was adjusted, the participants were instructed by the A.I to say the word 'Next' to move on with the tutorial. The next part of the tutorial was to learn the 'Ready' gesture. This gesture is used to prepare the participant for the air tap gesture and hand placement in front of the HoloLens' forward-facing camera. For this gesture, the participant had to hold out his/her finger and point it up. They were instructed to do this a couple of times before moving on. The next task was the air tap gesture in which they had to hold out his/her finger in the ready gesture and air tap. They were made to practice the gesture on crystal holograms which made a sound when tapped. The final gesture was 'Bloom'. For this, the participant held all their fingers together, and when ready, bloomed them open. This gesture brought up the home screen menu where they would exit and end the tutorial. The few other gestures that were not important to this particular study were the 'Scroll' and 'Voice command' gestures, which are used for scrolling through the AR interfaces and using verbal commands to select items instead of hand gestures, respectively.

Mission training. The mission training was designed by the researcher and provided an introduction to the interface, functions, and example tasks before initiating the missions on which data was collected. For this training, the researcher ensured that the device was properly fitted by the participant and walked through the whole practice mission with the participant. The participants started off by adjusting the HoloLens to fit them. The researcher ensured a secure yet comfortable fit and then directed them to start the practice mission. The participant then confirmed that all the crater holograms were displayed along with the lunar base.

The first training task was to navigate to the lunar base and conduct maintenance on the bacteria filter component. The participant identified the lunar base from the hologram, which appeared above the lunar base when looking through the HoloLens, and walked to the mechanical component. The next task was to 'gaze' at the image on the component to initiate the animations that would guide them in the maintenance task. The researcher instructed the participants to gaze at the image at a specific distance and angle which was necessitated to set the forward-facing camera on the image to initiate the animation. The participants then followed the checklist hologram (Figure 4) to conduct the practice maintenance task which involved unfastening a bolt on the component.


Maintenance Task Steps

4) Place in New Filter

5) Attach Bacteria Filter Casing

6) Tighten Both Fasters

Figure 4. Astronaut maintenance task.

The second training task was to navigate to a specific crater and collect a rock sample (Figure 5). This information was display on the checklist hologram. The participants were to navigate to the Mare Tranquillitatis crater and collect a generic green rock sample. This task tested the participants' understanding of the text description. The description was provided on the checklist hologram describing the sample they had to collect. This task also tested how well they could see the samples through the reflective mirrors.

Figure 5. Astronaut rock sample collection task.

The final training task was to navigate to a specific crater and initiate a call to mission control using the Remote Assist application. The task provided textual instruction on the checklist hologram which instructed the participants how to access the

Remote Assist application. Once the participants initiated the call, the researcher directed them on where to look and highlighted the rock sample to collect by circling the sample as it appeared upon the participant's FOV.

At the end of the training mission, the participants were asked if they were comfortable moving on to the next mission, or if they needed to try the training again to gain more experience. They were permitted to then either complete another training session or proceed to Mission 1, which was the first mission on which data was collected for the study.

Astronaut missions. The participants were to perform two sets of missions. The first mission, Mission 1, was intended to be of an intermediate difficulty level, and Mission 2 was designed to be a hard difficulty level. This was to gather data on how participants perform using the UI with different difficulty levels. The two missions are heavily documented below.

Mission 1. The intermediate mission compared to Mission 2 involved an easier maintenance task and rock samples to identify. This mission was easier due to the maintenance task having few steps, and the rock samples were easily distinguishable and identifiable.

Maintenance task. The participant started off the mission with navigating to the lunar base and installing a power-cell module into the bacteria filter component. For this task, the participant had to pick up the power-cell component that was on the table, install the component, and finally fasten the bolts to secure it. The steps to this task were displayed on the checklist hologram and displayed as an animation overlay on the component.

Navigation and rock sample collection task. The navigation task included navigating to the Mare Serenitatis, Mare Crisium, and Mare Cognitum craters by walking toward the holograms that labeled their locations within the environment. The participants used the tongs provided to gather the samples described in the checklist hologram. The first sample was the Breccia sample which was placed at the Mare Serenitatis crater. Its color was described to be light brown. The second sample was placed at the Mare Crisium crater. Its color was described to be medium grey to dark green. For the final crater, Mare Cognitum, there were more than two samples placed, and the participants had to initiate a remote call to mission control to be guided on which sample to collect.

Remote assistance task. Once the participant reached the final crater, Mare Cognitum, they were instructed by the task list to initiate a call to mission control. A ‘Click for instructions’ information box was displayed on how to initiate the call. The information contained in it was:

1. Use the bloom gesture and click the home screen icon.
2. Use the bloom gesture again to bring up the main menu.
3. Click on the remote assist icon.

These steps led participants to the application where they could start the call. Once they did this, the researcher at mission control guided them to selecting the rock sample. The guidance involved instructing the participant to orient the HoloLens toward the crater, which would provide the researcher with a clear image of the rock sample. The researcher then used the ‘ink’ tool to circle the sample to be collected. Finally, the researcher verified that the correct sample was acquired and told the participant the mission was complete.

Mission 2. The difficult mission was set to have a difficult maintenance task which involved multiple steps, and the rock samples were more difficult to distinguish and identify. The setup remained the same as Mission 1.

Maintenance task. The participant started the mission with navigating to the lunar base and was instructed to replace a filter on the bacteria filter component. For this task, the participant had to unfasten the bolts, remove the filter casing, take out the old filter (black in color), replace it with a new one (white in color) which they carried in their satchel, attach the filter casing, and finally, fasten the bolts to secure it. The steps to this task were displayed on the checklist hologram and displayed as an animation overlay on the component.

Navigation and rock sample collection task. The navigation task included navigating to the Mare Tranquillitatis, Mare Imbrium, and Mare Marginis. The participants used the same tools as was done in Mission 1. The first sample was the Olivine sample which was placed at the Mare Tranquillitatis crater. Its color was described to be emerald green to pale yellow green. The second sample was placed at the Mare Imbrium crater. Its color was described to be light grey, tan, or dark grey. For the final crater, Mare Marginis, there were more than two samples placed. The participants had to initiate a remote call to mission control to be guided on which sample to collect.

Remote assistance task. Once the participant reached the final crater, Mare Marginis, they were instructed by the task list to initiate a call to mission control. The participant followed the same procedure as was done in Mission 1.

Apparatus and Materials

Microsoft HoloLens. The Microsoft HoloLens is a fully self-contained holographic computer which is worn on the head of the user and runs the Windows 10 OS (Figure X) (Microsoft, 2019). This device contains see through holographic lenses with four forward-facing cameras. The lenses are contained within a visor which is tinted. It is a wireless device, and its battery life is approximately two to three hours of active use. It can also connect to the internet using it's built in Wi-Fi capabilities. Its size can be adjusted using the headband, and it weighs 579 grams (Microsoft, 2019). It can track the users gaze, gesture inputs, and voice commands. It has a limited FOV which is 34 degrees diagonally (Goode, 2019). This device can record videos in first person view which is then stored in the device's memory. These recordings can then be transferred to a personal computer wirelessly by using its Wi-Fi capabilities.

Figure 6. Microsoft HoloLens.

Lunar environment. In order to simulate a lunar environment for the astronauts, a room was chosen to recreate a lunar surface (Figure 7). A room in the Center of Faith and Spirituality building of the ERAU Daytona Beach campus was chosen as it provided a large area for the participants to navigate to different points without hindrance. The participants were subjected to a controlled environment in which the artificial lunar surface was protected within the confinements of the room.

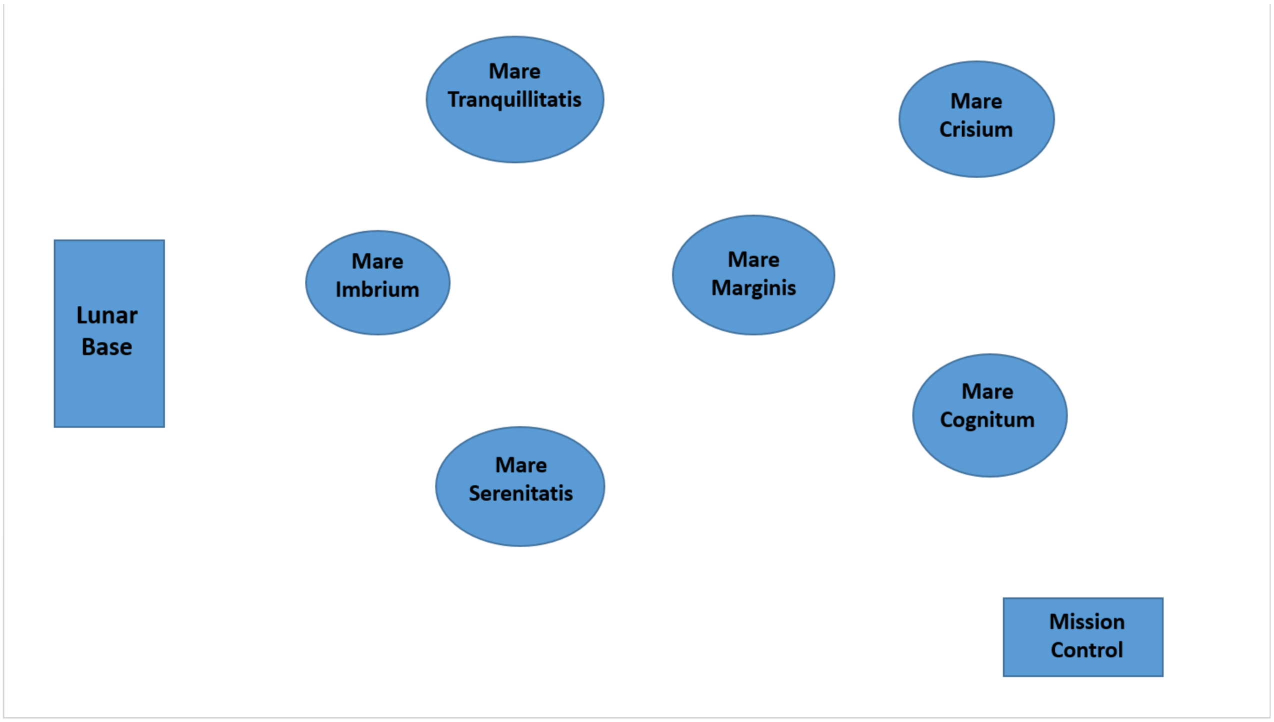
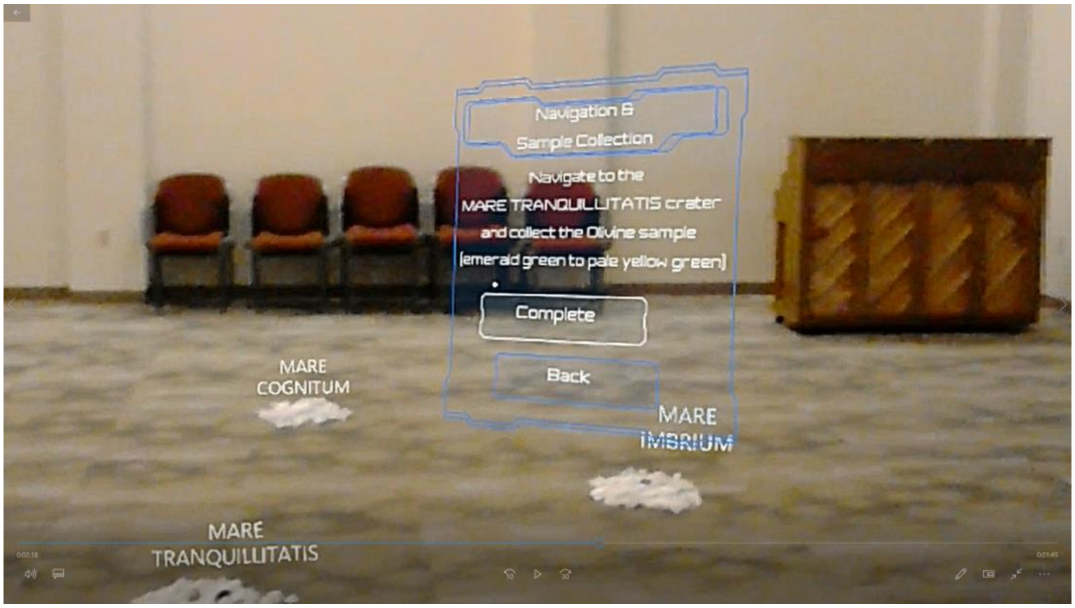


Figure 7. Lunar environment setup.

In order to simulate craters, medium size rock piles were set up. The rocks were a mild grey color which was purchased in large quantities from Home Depot. The craters chosen for this study were Mare Tranquillitatis, Mare Imbrium, Mare Marginis, Mare

Serenitatis, Mare Crisium, and Mare Cognitum. This information was displayed to the astronaut participants in the form of holograms which hovered over the specific craters through the HoloLens (Figure 8). The craters were spaced far apart to simulate the actual distance between them and to give participants the necessary room to navigate through them.


Navigation & Sample Collection

Navigate to the MARE TRANQUILLITATIS crater and collect the Olivine sample (emerald green to pale yellow green)

Figure 8. Lunar craters setup.

Collection samples. Lunar rock samples were placed as part of the rock sample collection tasks. The rocks were of different forms, these being Anorthosite, Olivine, Breccia, and Gabbro. These lunar rock samples are actual rock formations that are found on the lunar surface (Reid, A. 1974) which were purchased from an online website, Amazon.com, and some acquired from an ERAU professor with a degree in geology (Appendix F).

Lunar base. The lunar base consisted of a simple area enclosed with chairs around a table to separate it from the lunar craters. Resting on the table is the air filter component in which the participants had to perform maintenance tasks. The mockup of the lunar base was highly limited due to lack of space for an actual constructed structure.

Lunar bacteria filter component. The lunar bacteria filter component was a part of the fuel system filter retrieved from a large transport category airplane (Figure 9). It was converted by the researcher into an analog of a mechanical component that is used on the ISS. This component filters out the air aboard the ISS and could be used on a lunar base (SpaceRef Interactive Inc., n.d.). The right side of the component consisted of a filter which was to be replaced by the participants. For the first mission, the participants had to unscrew the housing and replace the air filter that had been contaminated. The left side of the component housed a power-cell which powered the complete system. For the second mission, the participants had to add a new power-cell to the component. The power-cell and filter casing needed to be inserted a specific way. Before starting the study, the researcher marked the two components with arrows in the direction they needed to be inserted.

Figure 9. Lunar bacteria filter component.

Astronaut tools. During the experiment on the simulated lunar surface, the participants had to conduct two separate maintenance tasks and three different rock sample collection procedures. For the maintenance task, the participants would carry the equipment, which was a replacement filter and a power-cell, in a satchel. The satchel was a small carry bag which was worn by the participants.

For the rock sample collection task, the participants used tongs similar to the ones used by astronauts on the Apollo missions. The participants would use this to pick up specific rock samples and place them in the satchel.

Population/Sample

The target population of the research was the astronauts who were supported by the Project Sidekick developed by NASA and Microsoft. This project allowed the astronauts aboard the ISS to conduct research and perform mechanical tasks using the HoloLens (Norris & Luo, 2016).

The sample of this exploratory study consisted of 22 participants. Both males and females were eligible for this experiment. The participants were required to be 18 years of age or older and have either completed or be currently taking the Turbine Engines academic course (AS-311) in the Aeronautical Science degree program at Embry-Riddle Aeronautical University (ERAU), Daytona Beach campus. The course requirement increased the probability that the participants possessed some knowledge on the air filter component used for the maintenance task. Further, this academic requirement approximated some of the basic requirements to become an astronaut in the NASA agency, to include having a science degree and being a pilot.

Ten of the 22 participants had some additional experiences that were used by the researcher to support the qualitative results: three participants had prior experience with the HoloLens, two participants had prior VR experience, three participants had an engineering background, one had a maintenance background, and one had a software development and HoloLens background.

IRB approval. The use of human participants required that the project was approved by the Institutional Review Board (IRB). Before starting the missions, the IRB required that the participants receive a full briefing, which includes information on the risks and hazards associated with AR and were given the opportunity to refuse participation. This was done prior to having the participants sign a consent form of participation (Appendix C). It was also required that participants could not suffer from motion sickness.

The briefing was to indicate to the participants that the researcher would not purposefully put them in a hazardous situation during the experiment. It was also stated that should they experience any discomfort such as dizziness, nausea, motion sickness etc., they should inform the experimenter. In that case, the participants would be instructed to take off the AR device and would be provided a comfortable area to rest until the discomfort dissipates and would be offered water to drink.

Information about the participants remained confidential, and no personal information was revealed in this research paper. The participants were given scientific enumeration (e.g., Participant A, Participant B) to be identified.

Sources of the Data

The data was collected from four data collection devices:

1. Microsoft HoloLens video recorder
2. NASA-TLX – in paper and pencil format
3. Researcher-developed usability survey
4. Researcher-developed usability interview

The video recording and NASA-TLX data were collected from the participants after each mission. The usability survey was administered after each mission, and the usability interview was administered after all the missions had been completed.

Data Collection Device

The data collection devices used during the experiment were separated into four categories—the HoloLens video capture data, NASA-TLX data, a usability survey, and a usability interview.

The HoloLens video capture provided video recording in first person view of the tasks performed by the participants. It recorded their verbal cues, hand gestures, FOV, task time, and task errors. The recording was initiated once the participants were ready to start the mission and ended upon mission completion.

Hart and Staveland's NASA-TLX (1988; Appendix H) is a subjective workload assessment tool comprised of six subjective workload subscales, which upon summation calculated an overall subjective workload scale. The subscales are mental demand, physical demand, temporal demand, performance, effort, and frustration. Each subscale was scored by having the participant indicate the degree of workload experienced using a response scale consisting of 20 gradations, ranging from very low to very high. The raw response scores on each subscale were used to compute the workload measures.

Two subjective usability survey questions, which were answered using paper and pencil format, were posed to each participant after each mission. The questions were as follows:

1. One a scale of 1 (hardest) to 10 (easiest), how easy did you find it to use the HoloLens for this mission?
2. One a scale of 1 (hardest) to 10 (easiest), how pleasing was the user interface to look at and work with for this mission?

Participants were asked to complete the survey based on how they felt after each mission.

A usability interview was developed by the researcher which provided qualitative data. This data was collected in the form of an interview at the end of the experiment. The questions were as follows:

1. Which feature of the device did you find most useful for you and why?

2. Please highlight any feature that you feel is missing from the app.
3. Talk about some of the good and bad aspects of the device and app.
4. Would you recommend any improvements to the device and app?

Treatment of Data

The HoloLens data was collected electronically through its built-in forward-facing camera. The video recording was uploaded to the researcher's personal laptop after each mission. The researcher extracted data from the video recordings of task errors based on using the AR UI and mission tasks. The data was collected on the number of times the participants made errors based on the information provided by the AR UI. The errors were considered to be: incorrectly using the AR UI, omitting checklist items, incompletion of a tasks, and performing the wrong tasks. The errors were separated into two categories: maintenance task errors and rock sample collection task errors. The researcher created an Excel spreadsheet and organized the data by mission number and errors for each variable. The researcher also made notes of error trends on a Microsoft Word document.

The NASA-TLX survey was administered to the participant after each mission. They were asked to complete the survey based on how they performed on that specific mission. It consists of six subjective scales with possible scores ranging from 1 (Very Low) to 20 (Very High), except for Performance which was 1 (Perfect) to 20 (Failure). The overall score was calculated by summing the scores of each of the six subscales. The researcher used the gradations on the response continuum for each subscale, which ranged from 1 to 20, to derive a score for each workload subscale. The researcher also calculated an overall workload scale. The researcher created an Excel spreadsheet and manually entered the NASA-TLX data for each subscale listed above into a table format. The data was organized by participant and mission number for each of the subscales.

A device usability survey was administered to the participants after each mission. They were asked to complete the survey based on two categories—the HoloLens device and the AR UI that contained all the task information in their FOV. The scale ranged from 1 (easiest) to 10 (hardest). The researcher created an Excel spreadsheet and manually entered the data of the missions into a table format. The data was organized by mission number and the rating outcome variable.

The usability interview provided the researcher with qualitative data. At the end of all the missions, the participant was interviewed. The researcher documented the interview responses manually using paper and pencil during the interview. The researcher then separated the data into two categories—HoloLens hardware usability and AR UI usability. The researcher created a table in Microsoft Word. The data was then organized by question, and participants' responses were combined to show trends for each category.

Descriptive Statistics

Descriptive statistics were used to describe outcomes on each of the NASA-TLX scales and overall subjective workload, the number of errors using the UI, number of task errors, and the usability survey ratings collected after every mission. The researcher used SPSS to calculate the means, standard deviations, medians, maximums, and minimums of all the collected data. Tables were created to describe all the data analyzed. The results of these descriptive statistics are reported in Chapter IV.

Hypothesis Testing

SPSS statistics software was used to conduct a one-tailed paired samples *t*-test to test each of the hypotheses:

1. The total number of errors committed using the AR UI in Mission 1 will exceed the number of errors using the AR UI in Mission 2.
2. The number of errors committed using the AR UI in completing the maintenance tasks in Mission 1 will exceed the number of errors committed using the AR UI in completing the maintenance tasks in Mission 2.
3. The number of errors committed using the AR UI in completing the rock sample collection tasks in Mission 1 will exceed the number of errors committed using the AR UI in completing the rock sample collection tasks in Mission 2.
4. The overall subjective workload in Mission 1 will exceed that of Mission 2.
5. Subjective mental demand in Mission 1 will exceed that of Mission 2.
6. Subjective physical demand in Mission 1 will exceed that of Mission 2.
7. Subjective temporal demand in Mission 1 will exceed that of Mission 2.
8. Subjective rating of performance in Mission 1 will be lower than that of Mission 2.
9. Subjective effort in Mission 1 will exceed that of Mission 2.
10. Subjective frustration in Mission 1 will exceed that of Mission 2.
11. Ratings of ease of using the HoloLens will be higher in Mission 2 than in Mission 1.

12. Ratings of pleasantness of using the AR UI will be higher in Mission 2 than in Mission 1.

The dependent measures were as follows: total number of UI errors, number of maintenance UI errors, number of rock sample collection UI errors, NASA-TLX (subscales and overall workload), ratings of HoloLens use, and ratings of UI use. The means of each measure were compared between Mission 1 and Mission 2 to indicate the presence of change over time and thus the extent of acclimation to using the HoloLens over time. A total of 12 *t*-tests were conducted. A *p*-value of less than 0.05 was used in each hypothesis test to indicate that there was sufficient evidence to reject the null hypothesis.

Qualitative Data

After concluding all missions, the participants completed a usability interview which was based on the experience of all the missions. The researcher administered this survey in the form of an interview to facilitate the participants' abilities to accurately describe their experiences. The survey allowed participants to describe their thoughts, recommendations, and feelings about the device hardware usability and AR UI usability. The researcher created a table in Microsoft Word and reported the data of the participants based on each interview question (Appendix J). The researcher divided the responses by the hardware and the AR software. These were further divided into sub-categories the hardware responses and AR software responses—a useful feature, a missing feature, and improvements. The qualitative data results were reported in depth in Chapter IV. Quotes from participants on improvements for the device and application were used to illustrate the advantages and disadvantages of the current HoloLens application as well as derive recommendations for future related studies and uses of the device.

Chapter IV

Results

Descriptive Statistics

NASA-TLX. Each post-mission NASA-TLX survey (Appendix I) consisted of six subjective scales and overall workload scale. Table 1 shows the results of the descriptive statistics for all participants with their workload variables in Mission 1. Table 2 shows the results of the descriptive statistics for all participants with their workload variables in Mission 2.

The researcher illustrated the evolution of the participant's scores from Mission 1 to Mission 2 by a bar chart (shown in Figure 10).

Table 1

Participants NASA-TLX in Mission 1

	Valid	Mean	SD	Min.	Max.
MD	22	4.77	4.231	1	14
PD	22	2.41	1.764	1	7
TD	22	2.73	2.004	1	8
PRF	22	3.55	3.363	1	13
EFF	22	3.95	3.709	1	15
FRU	22	3.50	3.233	1	13
OVE	22	20.91	14.596	7	61

Note. MD = Mental Demand, PD = Physical Demand, TD = Temporal Demand, PRF = Performance, EFF= Effort, FRU = Frustration, OVE = Overall. *Note:* Performance was rated from 1 (Perfect) to 20 (Failure).

Table 2

Participants NASA-TLX in Mission 2

	Valid	Mean	SD	Min.	Max.
MD	22	3.73	4.231	1	12
PD	22	2.50	1.764	1	11
TD	22	2.64	2.004	1	10
PRF	22	2.36	3.363	1	10
EFF	22	4.09	3.709	1	14
FRU	22	2.95	3.233	1	13
OVE	22	18.27	14.596	6	66

Note. MD = Mental Demand, PD = Physical Demand, TD = Temporal Demand, PRF = Performance, EFF= Effort, FRU = Frustration, OVE = Overall. *Note:* Performance was rated from 1 (Perfect) to 20 (Failure).

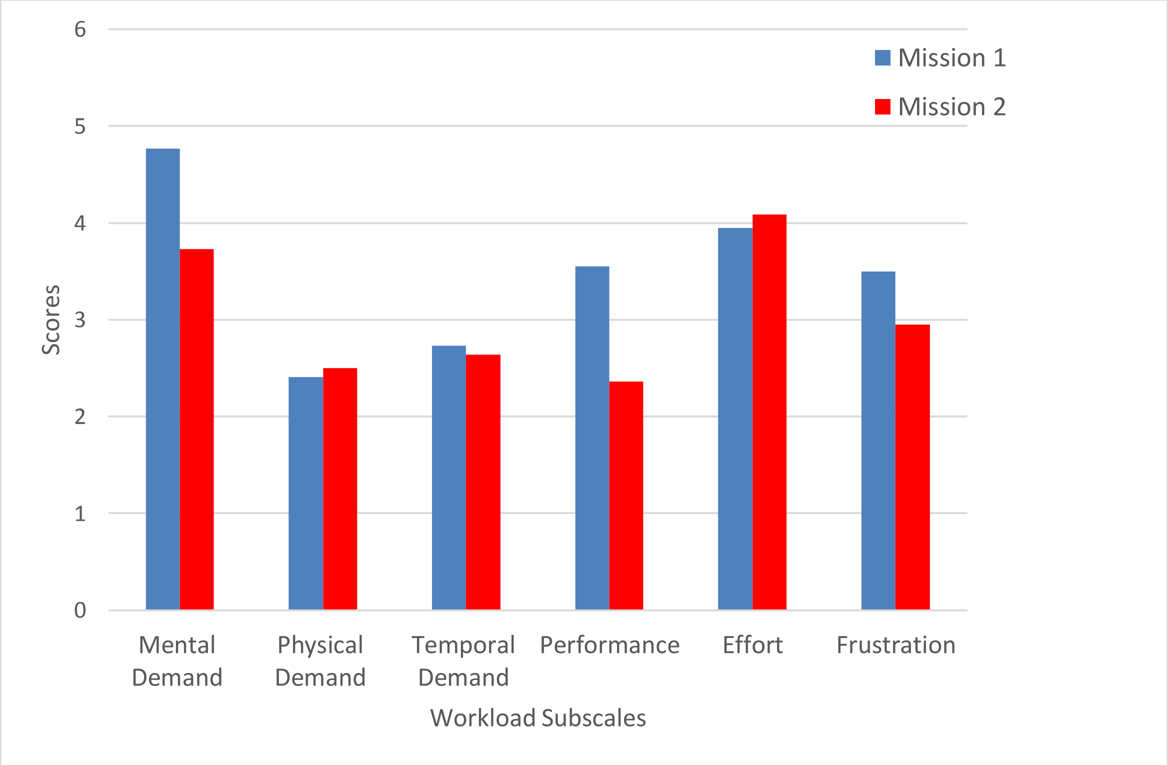


Figure 10. Participants' NASA-TLX in Mission 1 vs. Mission 2. *Note:* Performance was rated from 1 (Perfect) to 20 (Failure).

Usability rating survey. The participants' post-mission usability rating survey on the HoloLens and AR UI consisted of one question each. Table 3 shows the results of the descriptive statistics for all participants with both variables in Mission 1 and Mission 2.

Table 3

Participants' Usability Survey in Mission 1 and Mission 2

	Valid	Mean	SD	Min.	Max.
HoloLens Mission 1	22	8.09	1.342	6	10
HoloLens Mission 2	22	8.55	1.184	6	10
AR UI Mission 1	22	8.27	1.352	6	10
AR UI Mission 2	22	8.61	1.253	6	10

Note. AR = Augmented Reality, UI = User Interface.

Task errors. Through review of the HoloLens recordings, the researcher observed errors committed by the participants during the maintenance tasks and rock sample collection tasks. Table 4 shows the results of the descriptive statistics for number of task errors committed in Mission 1 and Mission 2.

Table 4

Number of Task Errors in Mission 1 and Mission 2

	Valid	Mean	SD	Min.	Max.
OVR Mission 1	22	4.73	4.641	0	20
OVR Mission 2	22	2.86	2.167	0	10
MX Mission 1	22	3.00	3.612	0	13
MX Mission 2	22	1.86	1.807	0	7
RSC Mission 1	22	1.73	1.609	0	7
RSC Mission 2	22	1.00	.816	0	3

Note. OVR = Overall, MX = Maintenance, RSC = Rock Sample Collection.

Hypothesis Testing

Total errors committed using the AR UI based on mission number. A one-tailed paired-samples *t*-test was used to test the null hypothesis that the total number of errors committed using the AR UI in Mission 1 (*M* = 4.73, *SD* = 4.641) would not exceed the total number of errors using the AR UI in Mission 2 (*M* = 2.86, *SD* = 2.167). The confidence interval percentage was set to 95%. Using an alpha level set at .05, there was a significant difference between the two missions *t*(21) = 1.850, *p* = .039. Thus, the null hypothesis was rejected. Cohen's *d* = 0.516, a medium effect size.

Errors committed using AR UI for maintenance task based on mission number. A one-tailed paired-samples *t*-test was used to test the null hypothesis that the number of errors committed using the AR UI on maintenance task in Mission 1 (*M* = 3.00, *SD* = 3.612) would not exceed the number of errors committed using the AR UI on maintenance task in Mission 2 (*M* = 1.86, *SD* = 1.807). The confidence interval percentage was set to 95%. Using an alpha level set at .05, there was no significant difference between the two missions *t*(21) = 1.543, *p* = .069. Thus, the null hypothesis was retained.

Errors committed using AR UI rock sample collection task based on mission number. A one-tailed paired-samples *t*-test was used to test the null hypothesis that the number of errors committed using the AR UI on rock sample collection in Mission 1 (*M* = 1.73, *SD* = 1.609) would not exceed the number of errors committed using the AR UI on rock sample collection in Mission 2 (*M* = 1.00, *SD* = .816). The confidence interval percentage was set to 95%. Using an alpha level set at .05, there was a significant difference between the two missions *t*(21) = 1.766, *p* = .046. Thus, the null hypothesis was rejected. Cohen's *d* = 0.572, a medium effect size.

NASA-TLX based on mission number. One-tailed paired-samples *t*-tests were used to test the null hypotheses that each of the subscales, except performance, and overall scores of the NASA-TLX in Mission 1 would not exceed those of Mission 2. A one-tailed paired-sample *t*-test was used to test the null hypothesis that the performance score in Mission 1 will be lower that of Mission 2. The confidence interval percentage was set to 95% for each test. Table 5 presents the paired-samples *t*-test results comparing Mission 1 and Mission 2. Using an alpha level of .05, none of the results were statistically significant. Thus, each of the null hypotheses were retained.

Table 5

Results of t-Tests Comparing Overall and Subscales of the NASA-TLX in Mission 1 and Mission 2

	Mission 1 Mean	Mission 2 Mean	N	*t*-value	Significance (one-tailed)
MD	4.77	3.73	22	1.519	.072
PD	2.41	2.50	22	-.257	.4
TD	2.73	2.64	22	.216	.415
PRF	3.55	2.36	22	1.629	.059
EFF	3.95	4.09	22	-.197	.422
FRU	3.50	2.95	22	.965	.172
OVE	20.91	18.27	22	1.103	.141

Note. MD = Mental Demand, PD = Physical Demand, TD = Temporal Demand, PRF = Performance, EFF= Effort, FRU = Frustration, OVE = Overall. PRF was rated from 1 (Perfect) to 20 (Failure).

Ease of HoloLens use based on mission number. A one-tailed paired-samples *t*-test was used to test the null hypothesis that the ratings of ease of using the HoloLens in Mission 2 (*M* = 8.55, *SD* = 1.184) would not exceed the ratings of ease of using the HoloLens in Mission 1(*M* = 8.09, *SD* = 1.342). The confidence interval percentage was set to 95%. There was a significant difference between the two missions *t*(21) = -2.109, *p* = .0235. Thus, the null hypothesis was rejected. Cohen's *d* = 0.363, a small effect size.

Pleasantness of using AR UI based on mission number. A one-tailed paired-samples *t*-test was used to test the null hypothesis that the ratings of pleasantness of using the AR UI in Mission 2 (*M* = 8.61, *SD* = 1.253) would not exceed the ratings of pleasantness of using the AR UI in Mission 1 (*M* = 8.27, *SD* = 1.352). The confidence interval percentage was set to 95%. Using an alpha level set at .05, there was a significant difference between the two missions $t(21) = -2.485$, $p = .0105$. Thus, the null hypothesis was rejected. Cohen's $d = 0.260$, a small effect size.

Qualitative Data

Microsoft HoloLens hardware usability. All 22 participants successfully completed the training without assistance from the researcher. No participants required a repetition of the training module. The data captured from the HoloLens video recordings documented errors committed while using it as well as interactions with the AR UI.

Gestures. Participants used gestures to interact with the checklist hologram for their missions. All participants found the gestures useful and easy to use. The researcher noted that there were not any instances where participants required help with gestures in either Mission 1 or Mission 2.

Fit of device. The HoloLens had to be worn by the participants to conduct their mission. The device involved a strap that would go around the forehead and to the back of the head. This strap could be tightened/loosened according to the size of the participants head. According to the interview, nine of the 22 participants had issues with the fit of the device. The participants had a hard time adjusting the device at the start of the study as it would keep slipping off their head. The researcher also noted that during the study three participants had to stop during the mission to adjust the device.

FOV. The HoloLens has a FOV that is limiting. The small FOV kept cutting off holograms when participants moved their head beyond the limitation. Based on the interview, nine out of the 22 participants suggested improvements in the FOV to see holograms and animations without being cut off. The researcher noted that animations on the maintenance task could not be initiated for some participants due to limited FOV and not placing hand gestures in the FOV.

Lens color distortion. The HoloLens consists of special combiner lenses in which projected images are displayed. The visor of the HoloLens is tinted; this caused inaccuracies in color discrimination that the researcher noted during the rock sample collection task. Ten out of the 22 participants collected the wrong sample during Mission 2. According to the interviews, two participants noted the color distortion caused by the visor.

AR UI usability. After concluding all missions, the participants completed a usability interview that was based on their experiences of all the missions.

Checklist. The checklist hologram provided a description of mission tasks to the user. Feedback from the usability interview showed all 22 participants provided both some good and bad aspects of the checklist. The good aspects were as follows: easy to use, overall checklist format, buttons, and overall AR UI improvements based on the user. The bad aspects are as follows: checklist could not be moved by the user, some lagging due to performance of the processor, buttons too close, and angled menu. From review of the HoloLens videos, the researcher noted that three of the 22 participants committed errors such as scrolling through tasks too fast and omitting items on the checklist.

Remote Assist. The Remote Assist application was used by participants to initiate a call to mission control for guidance on a rock sample collection task. The researcher observed that all participants completed this task with no errors. All 22 participants praised the remote assist function by stating that it provided them with clear audio, and the annotation over the sample to be collected was clear and precise. One participant suggested remote assistance being incorporated into the checklist UI to reduce gestures to initiate the application.

Animations. The animations provided guidance for maintenance tasks. The researcher noted that sometimes animations would not initiate due to the participant not placing the cursor on the image, image not within the FOV, and participants ignoring the animations and following textual instructions. Feedback from the usability interview showed good and bad aspects of the animations. The good aspects were that the animations overlaid the relevant maintenance component and helped complete the task by showing the participant where each component goes in the form of holograms. Based on the interview, two of the 22 participants gave positive feedback on the animations. The bad aspects included the limited FOV for animations, lag in animations initiating, and animations being slightly offset from the relevant component. Based on the interview, three of the 22 participants gave negative feedback on the animations.

Maintenance task-related errors. The bacteria filter component had two sides in which maintenance needed to be performed. To the right was the filter replacement task, and to the left the power-cell task. The participants were guided by the checklist on which side they should conduct the maintenance task. There were hardware issues observed by the researcher that some participants encountered. These issues are stated below.

Power-cell task. This task involved installing the power-cell into the bacteria filter component. During the study, the researcher noted that two participants requested help inserting the power-cell. The participants did not use the animation guidance, and the researcher intervened and assisted them.

Filter replacement task. This task involved removing the casing of the component and replacing the old filter with a new one. The researcher noted one participant did not add the new filter. The participant did not use the animation guidance, and the researcher intervened and assisted the participant.

Rock sample task-related errors. Craters were placed on the ground in the form of white rocks and their names labeled as holograms which participants used for navigation. The crater location and description of the samples to be collected were on the checklist. The researcher observed incorrect samples being collected by some participants during the study.

Mission 1. For this mission, participants had to collect the Breccia and Gabbro rock samples. The researcher observed that six participants out of 22 collected the incorrect sample based on the Breccia sample description. Feedback from the usability interview showed that participants were not provided with an accurate description of this particular sample. The researcher observed one participant collected the incorrect sample based on the Gabbro sample description. Feedback from the usability interview from this participant showed he was not provided with an accurate description of this particular sample

Mission 2. For this mission, participants had to collect the Olivine and Anorthosite rock samples. The researcher observed that eight out of 22 collected the incorrect sample based on the Olivine sample description. Feedback from the usability interview showed that participants had difficulties identifying the sample due to the tinted visor. The researcher also observed two out of 22 participants collected the incorrect sample based on the Anorthosite sample description. Feedback from the usability interview from these participants showed that they were not provided with an accurate description of this particular sample.

Chapter V

Discussion, Conclusions, and Recommendations

The data collected through this research allowed the researcher to make essential discussion points. Educated conclusions were drawn from the results of descriptive statistics, paired-samples *t*-tests, and qualitative data. There were also crucial results and recommendations derived from the usability interview at the end of the experiment where participants could give their input. The researcher used the feedback and improvements suggested to make recommendations for future studies on the subject.

Discussions

The study enabled the researcher to identify the fluctuations in workload subscales, improvement in usability, and reduction of task errors from Mission 1 to Mission 2, as well as generally assess the potential usefulness for AR in the astronautics domain.

Subjective workload. The descriptive statistics acquired from the NASA-TLX determined that the average overall workload was numerically lower in Mission 2 than it was in Mission 1. Also, there were trends for Mental Demand, Temporal Demand, and Frustration scores to decrease from Mission 2 to Mission 1. The trends obtained were similar to those found in the study which used AR for aircraft maintenance training and operations in which the participants performed oil checks on an airplane, where the workload subscale scores remained low while using AR (De Crescenzio et al., 2011). In another study done by Braly, Nuernberger, & Kim (2019), participants conducted procedural tasks on a spaceflight hardware using AR which showed similar NASA-TLX results. Braly, Nuernberger, & Kim (2019) results showed that mental and temporal workload scores were low when using AR. Therefore, astronauts or even wearers in other complex or high risk environments will benefit in using AR for their respective procedural tasks.

There was also a trend for participants to experience an increase in Physical Demand and Effort in Mission 2, likely due to the increase in task difficulty level. Specifically, the second mission featured an increase in number of checklist tasks for the maintenance component and reduced discriminability in rock samples. The level of difficulty was increased in Mission 2 to replicate the high physical workload astronauts encounter in space. Astronauts on missions are tasked with high workload, which include the maintenance of technical systems and conducting science and medical experiments (Manzey & Lorenz, 1999). A further possible reason for the increased physical demand and effort may stem from the continued strain of wearing the HoloLens. Corroborating this finding is the fact that several participants reported issues with the fit of the device, such as it slipping off their head and needing to make fit adjustments during the missions.

Lastly, the means of the performance subscale scores, which ranged from 1 (Perfect) to 20 (Failure), showed a trend toward improvement from Mission 1 to Mission 2, possibly due to participants feeling they had a great amount of exposure in using AR to complete the tasks. The researcher theorized that participants felt more confident in their performance, due to accumulating experience with the device and perhaps increased sense of benefit from using it. This acclimation in using the device can be related to a study done in Cognitive, Performance, and System Issues for Augmented Reality Applications in Manufacturing and Maintenance by Neumann and Majoros (2002). The authors state that AR can help in recalling and learning the information presented. This recall and learning according to them is due to the association of a virtual object with a real world task, which helps the users remember a list of items (Neumann and Majoros 2002).

The generally low overall workload scores and lack of statistically significant differences in workload ratings between Mission 1 and Mission 2 may be because the use of AR generally made the tasks easier across both missions. The AR UI was designed to guide participants through the steps of each task in proper sequence. In a study done by Crescenzio et al. (2011), the results from using AR to perform oil checks on a small airplane showed that sequential task information reduced mental workload. In another study done by Hoover (2018), results from using the HoloLens showed that participants felt that AR instructions reduced their mental workload. Therefore, having tasks and procedures in the form of AR could likely benefit astronauts tasked with high workload. Currently in the space industry, Lockheed Martin is using the HoloLens to view procedures of the Orion's assembly manual. Since technicians have to constantly flip back and forth between instructions, the HoloLens provides them in AR which makes it easier to use (Tarantola, 2019). The researcher believes that there could have been statistically significant differences observed with an increase in the sample size, coupled with an increase in the difficulty and number of tasks.

Task errors. The descriptive statistics acquired from the participant task errors determined that the average overall number of errors was significantly lower in Mission 2 compared to Mission 1. Based on the hypothesis test, there was also a significant reduction in the mean number of errors in the rock sample collection task in Mission 2.

The decline in errors in Mission 2 likely reflects how participants became more familiar with the UI and had a better understanding of the procedural information, even though the task in Mission 2 was designed to be more difficult. As with the maintenance task, the rock collection sample task was designed to be more difficult, by having rock samples that were more difficult to distinguish and identify. The researcher theorizes that the participants became acclimated with the procedures and performed better in Mission 2. In the study by De Crescenzio et al. (2011) on using AR for maintenance training and operations support, the authors' results showed that providing sequential task instructions helped in task efficiency as participants were accustomed to always being guided with the information present in the UI. Another reason the researcher theorizes for the decline in errors is due to information recall from Mission 1 to Mission 2. The general structure of the tasks remained the same apart from their difficulty. Therefore, AR helped participants become accustomed to how the tasks should be performed. Neumann and Majoros (2002) state that AR aids in recall and learning by associating virtual objects with real world objects thus creating the basis for users to recall information from their memory.

The researcher looked into task errors committed in the maintenance task. There was no significant reduction in the mean number of errors committed in the maintenance task; however, it is an important observation that the mean number of errors in both missions was extremely low in this task. Further, even though the second mission's maintenance task was more complex, the error rate remained low. This increase in difficulty may have overridden any statistical improvement in the error rate. Importantly, the low error rate despite the increased task difficulty supports the idea that the use of the

HoloLens and its accompanying AR UI aided the participants in their task completion. The researcher theorized that this was due to the procedural information provided to the participants in the form of AR. Participants could complete the tasks successfully with the information present to them not just in text but also in holographic animations. This holographic textual and animation information guide participants by visually showing them how to perform the tasks. In a study done by Braly, Nuernberger, & Kim (2019) on how AR improves procedural work on an ISS component, similar results in using an AR checklist and holographic animations suggested that NASA spaceflight operations will benefit from using AR technology to display procedural information, thus reducing error.

Despite the increase in task difficulty, performance improved, an effect that could be explained by increased experience with the task (e.g., better understanding of the rock sample description) as well as continued assistance from the HoloLens and its UI. The researcher theorized that continuous assistance from the HoloLens and its UI in the form of checklists, animations, and most of all the Remote Assist function helped them with the tasks. According to the participants, the checklist provided them with enough textual information that was clear in completing tasks, the animations guided them in the maintenance task by overlaying holograms on the component showing them how to perform the task, and the Remote Assist function helped the participant contact mission control to aid them in collecting a rock sample. Astronauts on board the ISS have used the HoloLens which displays animated holographic illustrations on top of objects to help them perform tasks (NASA and Microsoft Partner to Develop Sidekick, 2015). These astronauts also used the remote assistance feature to contact an expert on the ground who provided real-time guidance in completing tasks (NASA and Microsoft Partner to

Develop Sidekick, 2015). In an interview with astronaut Scott Kelly, he states that having an expert's guidance using the remote assistance function, where the experts can not only provide information but also see what the astronauts are seeing and make annotations, helps astronauts in the completion of tasks. The researcher theorizes that this guidance will help in minimizing task errors. Thus, results from these comparisons suggest that use of AR can potentially benefit astronauts by providing procedural task information and thus reducing error (Braly, Nuernberger, & Kim, 2019).

Positive assessments of the HoloLens hardware and UI usability. Based on the feedback from participants in both the usability survey and interview, there were several positive aspects of the present design of the HoloLens and its UI. The usability survey determined that ratings in terms of ease of use of the HoloLens and its UI were generally high in both missions, with a slight increase in Mission 2. The participants likely became familiar with the device and it's UI as a function of time. According to the usability interview results (Appendix J), many of the participants commented on the ease of use of the device by praising its functions, stating that the gestures were easy to use and very responsive. They stated that the holograms displayed were clear, and there was minimal lagging of the device. A study done by Evans et al. (2017) developed their own application which used the HoloLens for an AR assembly task. The results in their study showed that the hardware was a viable platform to develop the application (Evans et al., 2017).

The results acquired from the ratings of pleasantness of using the UI were significantly higher in Mission 2 than Mission 1. From the usability survey, the participants stated that the checklist in the FOV provided them the ease of completing tasks, and they could be manipulated using hand gestures. The researcher believes the checklist in the FOV feature supports the ratings of pleasantness of the AR UI and the ease of use of the device. The researcher concludes that having information displayed in the FOV provides hands-free information while performing tasks. The researcher theorizes that this feature helps in performing tasks efficiently without having to hold on to procedural information or looking at a computer screen. According to astronaut Scott Kelly's experience with the HoloLens, having the procedures displayed in the FOV, as opposed to looking at a computer screen or iPad, is more helpful for astronauts (Franzen, 2015). According to NASA, the HoloLens which will display procedural information to the astronauts, will improve task efficiency (Norris & Luo, 2016). This display of procedures in the users FOV would likely minimize eye movements and help astronauts in faster task completion times and minimize errors (Braly, Nuernberger, & Kim, 2019).

The checklist was well received and was displayed in a fashion that was easy for them to understand and follow. It made it easy to read task information and was hands free. The animations that were incorporated in the maintenance tasks was also well received and provided them with a visual solution on what needed to be accomplished. The researcher concluded that this likely helped in reducing task error among the missions (Braly, Nuernberger, & Kim, 2019). The checklist hologram helped in task performance for the participants since it was in the form of AR and directly within their FOV. According to astronaut Scott Kelly, onboard the ISS, astronauts use computer screens and iPads to view procedures. He states, "Having procedures right in your field-of-view would be helpful" (Franzen, 2015).

The Remote Assist application was praised by the participants in the usability interview. The researcher observed that there was not a single error among all 22 participants when using the Remote Assist application to collect a specific rock sample. The researcher concluded that this was due to the aid provided by a simulated expert to assist the participant by making annotations and guiding them through the task. The results were supported by a statement from astronaut Scott Kelly's description on how the Remote Assist feature will aid astronauts aboard the ISS by providing them guidance on a task from an expert on the ground (Franzen, 2015). According to Jeff Norris, the project manager for the HoloLens at NASA, the remote assistance mode connects the astronaut onboard the ISS to an expert on the ground to provide guidance with unfamiliar tasks (Metz, 2015). The application of this mode on the ISS will likely help astronauts on future missions.

Negative assessments of the HoloLens hardware and UI usability. Participants expressed concern over some drawbacks and limitations of the HoloLens hardware, and the researcher observed some participant behaviors that signaled poor usability. Generally, troublesome aspects included the limited FOV, fit of the device, color distortion of real-world objects due to the tinted visor, and lack of customizability.

From the usability interview, the most frequently recommended improvement involved permitting the wearer to manipulate the location of the checklist interface within their FOV, which would prevent it from obstructing real-world objects while performing tasks. This recommendation was voiced by the majority of the participants. Additional comments consisted of minimal lags that were experienced with the device, the fit of the device, and improvements to the image quality of animations. Krevelen (2007) conducts a review in the field of AR and draws conclusions on its limitation. The author concluded that since the technology is fairly new, a lot of considerations need to be taken into account such as improving the FOV, cost, weight, power usage, and ergonomics (Krevelen, 2007). The researcher theorizes that incorporating a powerful processor will increase the performance of the device to support all of the resource demands made upon it. The device needs to be able to support all the astronaut checklists and emergency procedures without failing, especially in an emergency situation when the astronaut needs to access the emergency checklist procedure to resolve the issue. The HoloLens has its own custom Holographic Processing Unit built by Microsoft (Microsoft, 2019). This processor is currently upgraded by Microsoft in the HoloLens 2 with a second generation processor which provides a better quality in holograms (Goode, 2019), which would help in minimizing the lag of the processor even more and improving the quality of animations during tasks. Another improvement to the HoloLens 2 is the fit of the device. The HoloLens was front heavy as a lot of the components were loaded in the front (Goode, 2019). Results from the usability interview and the researcher's observations showed that the device needed to be adjusted at times during the experiment. The researcher theorized that this could be possible due to the fit of the device. The components in the HoloLens 2 are split up between the front and back making it balanced and comfortable for the user (Goode, 2019).

Other improvements suggested were incorporation of voice commands to manipulate and scroll through the checklist, improving the degree to which animations accurately overlay real world objects, and using images to enhance the verbal description of task-relevant objects. Therefore, adjustments need to be made to the AR UI before it can be deployed and widely accepted by end users for their specific goals. According to Jeff Norris, the project manager for the HoloLens at NASA, the HoloLens makes it easier for astronauts to complete challenging tasks such as inventory management onboard the ISS, but there are challenges associated with building AR applications such as how the menu should look and how the user should interact with it (Metz, 2015). In order to be completely integrated for astronauts they would need specific menu designs, checklist procedures, animation guidance overlays, and gestures that match the tasks for their missions. Astronauts would also require an emergency procedures checklist, should one arise, since spaceflight accidents and mission failures can result from incorrect procedure execution (Braly, Nuernberger, & Kim, 2019). Another specific design for astronauts would be the remote assistance feature. In a situation where an astronaut is unfamiliar with a task, they should be able to get in contact with an expert on the ground to provide guidance (Metz, 2017).

The researcher also recommends future UI-specific developments that would be advantageous to astronauts such as a personalized mission checklist to assist them with the tasks they are about to undergo. These personalized checklists would contain procedures relating to performing maintenance tasks (SpaceRef Interactive Inc., n.d.), conduction experiments, and even building lunar outposts (Dunbar, 2019). Astronauts' missions are planned prior to their start (USRA, 2019). Therefore, all the necessary documents and checklists should be available to them in AR. Specific interfaces should be created with information displayed that is required for tasks the user performs (Metz, 2015). Hence, further development and tests need to be done with issues regarding userfriendly interfaces (Krevelen, 2007). Therefore, AR has yet to advance and with more tests and development it will improve with time (Khor et al., 2016).

Conclusions

Based on the collection of anecdotal evidence collected through the participants' usability interview, the data obtained during this research, and the majority of the analyses conducted, the researcher's conclusion is supported that AR can support astronaut task completion during lunar missions. The researcher aimed to contribute findings that would support the gap between the existing literature of factors such as usability, task errors, and workload (Norris & Luo, 2016). The results derived from descriptive statistics and hypothesis testing showed improvements across exposures to the HoloLens platform in task performance, workload, and usability among the participants. Participants showed a decrease in overall workload, reduction of task errors, and increase in usability of the device and UI. The researcher concluded that using an AR device which displayed procedural information helped in task performance that included textual and holographic animation information on tasks and helped in completion and reduction of error (Neumann & Majoros, 2002). Participants in this study completed all the tasks with no omissions and in the correct order according to the checklist, similar to prior research by Tatić & Tešić (2017).

The anecdotal data collected regarding UI usability was specific to this study and did not reflect any findings from existing literature. Limited research has been done on interfaces and ergonomics in using AR for tasks (Krevelen, 2007). This study helped to contribute answers to this. The researcher concluded that interfaces have to be specifically designed to match the astronauts and their respective missions (Metz, 2015).

Astronaut missions are carefully planned prior to their start (USRA, 2019). This is to ensure the outcomes will be successful. Therefore the AR interfaces developed should contain all the necessary information for a specific mission the astronaut is undertaking. The information should include all the necessary documents and checklists to guide them through their assigned tasks.

The researcher also concluded that future research should further incorporate and increase testing of AR for astronauts. Currently, NASA is preparing astronauts to land on the moon by 2024 (Dunbar, 2019). The Artemis lunar exploration program will provide the bases for introducing and demonstrating new technology. This will eventually lead to perfecting the technology on the lunar surface thus paving the way to sending astronauts to Mars. The testing of AR technology for astronauts will be critical during the proposed lunar missions. During these missions, astronauts will be tasked with building a sustainable presence to support future human outposts, explore larger parts of the lunar surface, and manufacture and build structures with materials found on the moon (Dunbar, 2019). AR technology has shown to be beneficial in the manufacturing industry. An example of this is Boeing using the Hololens to manufacture the Starliner transport module for the ISS (MacPhedran, 2018). Therefore, AR can assist astronauts in their future lunar missions in manufacturing and building.

With the Artemis lunar exploration program being incorporated, so does next generation spacesuits (Mahoney, 2019). The researcher concluded that AR should be incorporated as a part of an astronaut's spacesuit. According to NASA, the 21st century moonwalkers will be able to accomplish more complex tasks than their predecessors due to the technological advances. The incorporation of AR will be key to accomplish these complex tasks and will have a positive impact on the space industry (Ramsey, 2015). Lastly, NASA plans to customize and test spacesuits for each astronaut before they step on the lunar surface (Mahoney, 2019). This customization could likely involve AR UI being customized to specific missions astronauts undergo.

The usability information provided by the participants can provide support for the use of AR for complex tasks; AR devices can have a positive impact as it has been previously shown to be a great asset in the education, industrial, and medical fields (Dey, Billinghurst, Lindeman, & Swan II, 2018), as well as the space industry, such as Project Sidekick (Norris & Luo, 2016) and manufacturing the Starliner transport module for the ISS (MacPhedran, 2018). Therefore, the results from the present study support revisiting the use of AR in future lunar missions.

Recommendations

There were several lessons learned from this study. The researcher and participants made several recommendations that could help improve the quality of future research.

User interface. The improvement of the UI is a primary recommendation to take into consideration when designing future studies. The researcher along with some recommendations from participants would make improvements to the existing UI.

The first major change would be to give the user the ability to place the AR checklist interface anywhere in their FOV. This flexibility would give them the freedom to use either hand to perform gestures. The ability to reposition the AR checklist interface would also prevent the AR checklist hologram from overlaying itself on real world objects and cause less of an obstruction when performing tasks. Omitting obstructions will also prevent the participant from being distracted while performing a task.

The second change would be to incorporate the Remote Assist application into the UI. During the missions, participants had to use a series of gestures to navigate to the home menu and start the call. Future researchers could incorporate the remote assistance application into the UI created in Unity.

Finally, future researchers should look into developing an interface that would replicate an astronaut's actual checklist. Doing so will add to the authenticity of the study and can help in refinement of the current checklist. This refinement would include separate menus for maintenance tasks where the participant would have a choice from a list of maintenance tasks, an emergency protocol checklist, the tools required for the chosen task, and the time to complete the task (SpaceRef Interactive Inc., n.d.) when translated into AR. The researcher also recommends minor adjustments to manipulation buttons which could include voice commands which will help in advancing though tasks without the use of hand gestures and the addition of images (in this case rock samples) to the AR UI, to help with identifying real world samples.

HoloLens hardware. Fitting issues were encountered during the study with the HoloLens. The device would slide down the participants head causing them to stop and adjust it. Future researchers should try to incorporate the HoloLens into a helmet that could be customizable. This would ensure that it constantly stays in place on the participant's head. To avoid problems with the system lagging, the device should be rebooted once the participant has completed a mission.

Since the HoloLens 1 was used to conduct the study, there were limitations on the FOV. Participants needed to get used to the limited FOV and practice the placement of their hands for gestures. The limited FOV caused multiple errors using the UI. Future recommendations would be to have the participant practice more and get accustomed to the limiting FOV. Another recommendation would be to use the HoloLens 2 as it has a wider FOV along with hand tracking. The HoloLens 2 has improved on the FOV design by increasing it to 52 degrees as compared to 34 degrees on the HoloLens (Goode, 2019, para. 22).

Maintenance task. Due to the limiting factor of astronaut population on this research, the maintenance tasks used were extremely easy. The researcher recommends advanced level tasks for future studies with additional animations and checklists for guidance. Advance level tasks would include longer maintenance tasks where participants would have to refer to more manuals and the incorporation of an emergency situation during the task. The mechanical components used in future studies should be designed to reflect actual components astronauts work on the ISS.

Guidance animations played a key role in this task. However, a few participants struggled to initiate the animations. This was due to the distance between the trigger image and the HoloLens position, since participants were of varying height. The researcher suggests having an expert who is experienced with Vuforia (animation triggers) or any other animation software that can be imported into Unity, for development of animations. Experts in this field will be able to create and import animations into Unity from other programs designed specifically for animations (Autodesk 3ds Max, Blender, etc.). Additional suggestions would be to improve animations by making adjustments in the Unity code by adding accurate measurements between the real world object and the holograms to overlay them on the component.

A secondary recommendation would be to have the Remote Assist call available at all times during tasks. Some participants required help recognizing and aligning parts of the component. This could reflect an abnormal task an astronaut would have to perform on the ISS. To solve this, a remote call to mission control with experts on Earth would provide guidance.

Lastly, contingencies or simulated emergencies were not incorporated in the study. Future researchers should incorporate simulated emergencies during maintenance tasks to reflect real-life unexpected emergencies that occur on the ISS. This would also include incorporating emergency procedures into the UI and a quick way to pull up the information to resolve issue.

Navigation and rock sample collection task. Due to limited financial resources, a room was reserved and configured to replicate the lunar surface. The configured room made it easy for participants to locate and navigate to craters. Future researchers should use a larger room and add a lunar outpost module. This module would have an enclosure in which the participant would have to navigate to the maintenance station to perform the tasks. This environment would replicate what an actual lunar base would look like. Further recommendations to support the navigation would be to incorporate directional arrows as holograms in the HoloLens.

A secondary recommendation would be to incorporate pictorial descriptions of rock samples. Participants who are unfamiliar with geology found the descriptions of the samples to be too vague and collected the wrong sample. The researcher suggests adding a picture along with descriptions of the sample for future studies.

Distortion of color by the HoloLens should be taken into consideration in the future with rock sample colors. The HoloLens visor tint causes the distortion of color. Participants were hesitating on the Olivine rock sample as the HoloLens visor distorted its color. The participants could not match its color accurately with the description provided.

Artificial lunar base and terrain. The primary recommendation was to use a more realistic environment to conduct astronaut missions, to include expanded terrain, an outpost, a space suit, astronaut tools, and conducting the study in a zero gravity environment. Participants should also have some astronaut training background to further help in development AR usability. Expanded terrain and a lunar outpost would increase navigation distance and placement of world holograms for the astronauts to follow. Having an outpost with multiple rooms would help in the navigation process, as stated in the navigation task.

Participant recommendations. At the end of all missions, participants were asked to complete a usability survey in the form of an interview by the researcher. The participants made a few recommendations of their own. One participant suggested the incorporation of voice commands for checklists tasks. The participant recommended this modification so that he could continue holding the maintenance components and use voice commands to advance to the next task instead of using the airtap gesture. This feature would help when astronauts need to use both hands on certain tasks.

The participants also suggested being able to move and manipulate the checklist hologram, as stated in the user interface section, to suit their needs. Some participants found it frustrating that the checklist followed their head movements as it disturbed them while performing tasks.

Finally, the participants claimed they enjoyed using the HoloLens and performing the tasks. Some participants never had any experience with AR or VR and praised the potential it has for the future.

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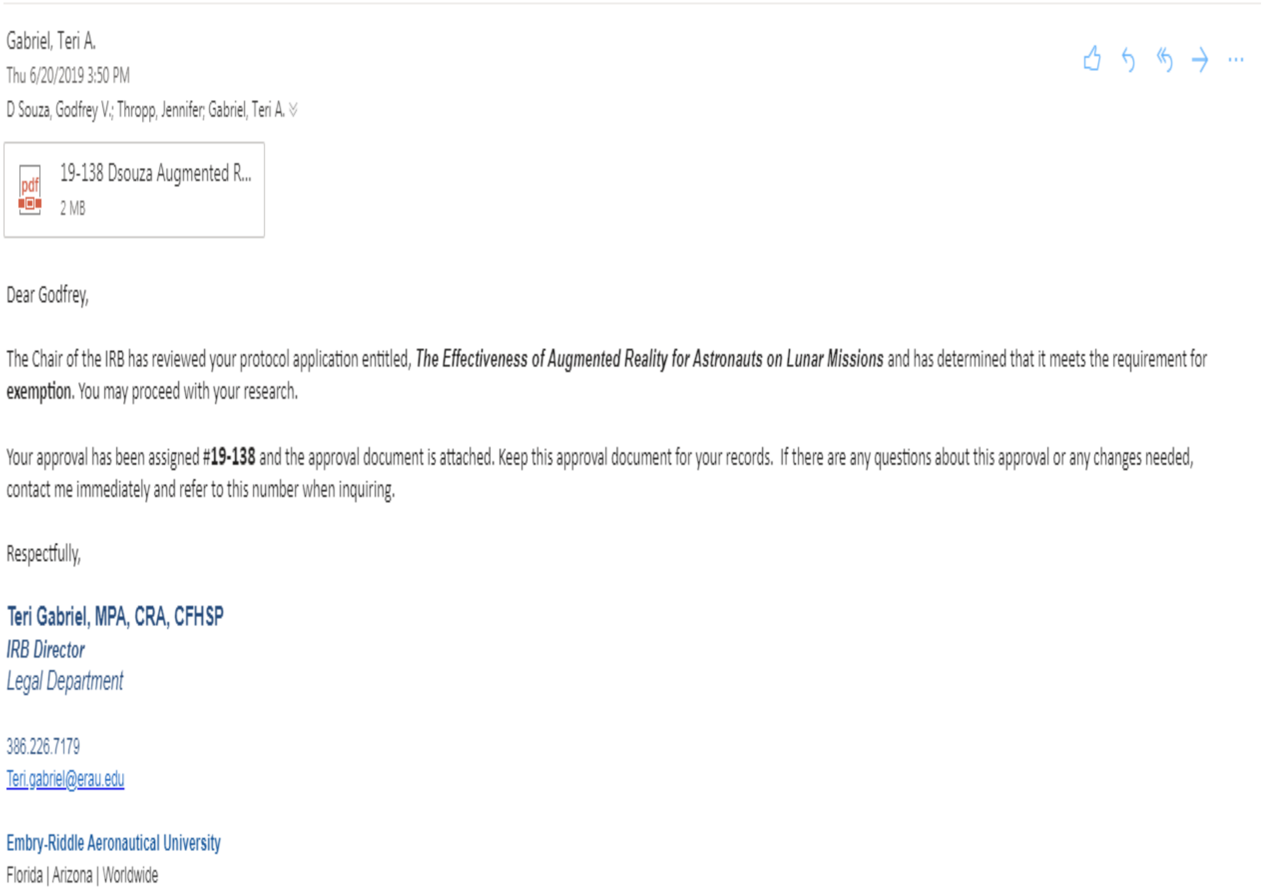
Appendix A

Permission to Conduct Research



Gabriel, Teri A.
Thu 6/20/2019 3:50 PM
D Souza, Godfrey V.; Thropp, Jennifer; Gabriel, Teri A.

19-138 Dsouza Augmented R...
2 MB

Dear Godfrey,

The Chair of the IRB has reviewed your protocol application entitled, ***The Effectiveness of Augmented Reality for Astronauts on Lunar Missions*** and has determined that it meets the requirement for **exemption**. You may proceed with your research.

Your approval has been assigned **#19-138** and the approval document is attached. Keep this approval document for your records. If there are any questions about this approval or any changes needed, contact me immediately and refer to this number when inquiring.

Respectfully,

Teri Gabriel, MPA, CRA, CFHSP
IRB Director
Legal Department

386.226.7179
Teri.gabriel@erau.edu

Embry-Riddle Aeronautical University
Florida | Arizona | Worldwide

Appendix B

Recruitment Flyer

PARTICIPANTS NEEDED FOR STUDYING THE EFFECTIVENESS OF AUGMENTED REALITY FOR ASTRONAUTS ON LUNAR MISSIONS

Participants will wear a head mounted Augmented Reality device and complete a series of tasks on a simulated lunar surface.

Tasks will include Navigation, Rock sample collection, and an assembly task.

The study will take approximately 1 to 1.5 hours and participants will be compensated $20 for completing the study.

Must be 18 years or older to Participate and have completed or currently taking AS-311(Turbine Engines).

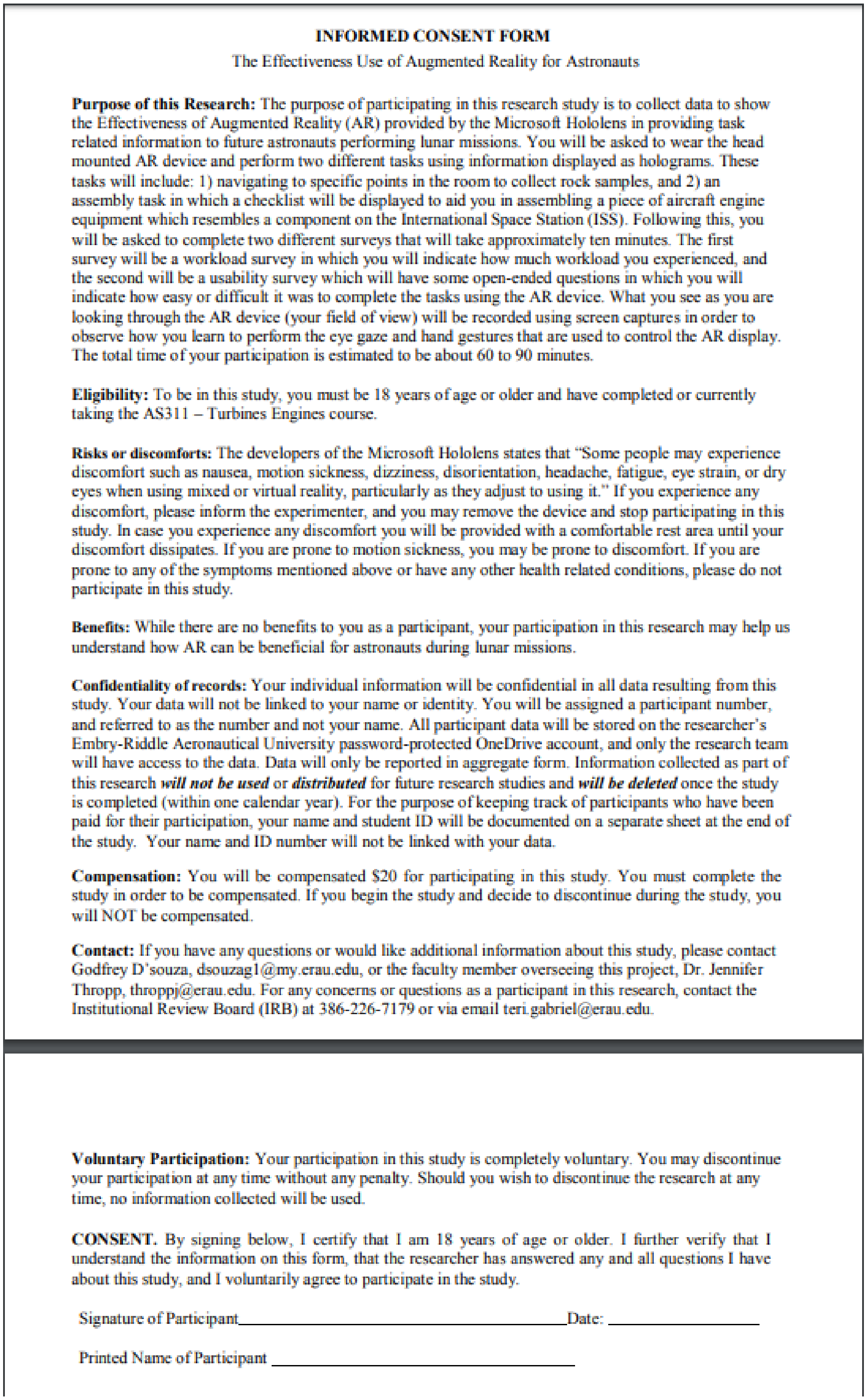
Risks could include discomfort such as nausea, motion sickness, dizziness, disorientation, headache, fatigue, eye strain, or dry eyes when using mixed or virtual reality.

If interested contact

Godfrey D'souza at dsouzag1@my.erau.edu

Appendix C

Informed Consent



INFORMED CONSENT FORM

The Effectiveness Use of Augmented Reality for Astronauts

Purpose of this Research: The purpose of participating in this research study is to collect data to show the Effectiveness of Augmented Reality (AR) provided by the Microsoft Hololens in providing task related information to future astronauts performing lunar missions. You will be asked to wear the head mounted AR device and perform two different tasks using information displayed as holograms. These tasks will include: 1) navigating to specific points in the room to collect rock samples, and 2) an assembly task in which a checklist will be displayed to aid you in assembling a piece of aircraft engine equipment which resembles a component on the International Space Station (ISS). Following this, you will be asked to complete two different surveys that will take approximately ten minutes. The first survey will be a workload survey in which you will indicate how much workload you experienced, and the second will be a usability survey which will have some open-ended questions in which you will indicate how easy or difficult it was to complete the tasks using the AR device. What you see as you are looking through the AR device (your field of view) will be recorded using screen captures in order to observe how you learn to perform the eye gaze and hand gestures that are used to control the AR display. The total time of your participation is estimated to be about 60 to 90 minutes.

Eligibility: To be in this study, you must be 18 years of age or older and have completed or currently taking the AS311 – Turbines Engines course.

Risks or discomforts: The developers of the Microsoft Hololens states that "Some people may experience discomfort such as nausea, motion sickness, dizziness, disorientation, headache, fatigue, eye strain, or dry eyes when using mixed or virtual reality, particularly as they adjust to using it." If you experience any discomfort, please inform the experimenter, and you may remove the device and stop participating in this study. In case you experience any discomfort you will be provided with a comfortable rest area until your discomfort dissipates. If you are prone to motion sickness, you may be prone to discomfort. If you are prone to any of the symptoms mentioned above or have any other health related conditions, please do not participate in this study.

Benefits: While there are no benefits to you as a participant, your participation in this research may help us understand how AR can be beneficial for astronauts during lunar missions.

Confidentiality of records: Your individual information will be confidential in all data resulting from this study. Your data will not be linked to your name or identity. You will be assigned a participant number, and referred to as the number and not your name. All participant data will be stored on the researcher's Embry-Riddle Aeronautical University password-protected OneDrive account, and only the research team will have access to the data. Data will only be reported in aggregate form. Information collected as part of this research ***will not be used*** or ***distributed*** for future research studies and ***will be deleted*** once the study is completed (within one calendar year). For the purpose of keeping track of participants who have been paid for their participation, your name and student ID will be documented on a separate sheet at the end of the study. Your name and ID number will not be linked with your data.

Compensation: You will be compensated $20 for participating in this study. You must complete the study in order to be compensated. If you begin the study and decide to discontinue during the study, you will NOT be compensated.

Contact: If you have any questions or would like additional information about this study, please contact Godfrey D'souza, dsouzag1@my.erau.edu, or the faculty member overseeing this project, Dr. Jennifer Thropp, thropj@erau.edu. For any concerns or questions as a participant in this research, contact the Institutional Review Board (IRB) at 386-226-7179 or via email teri.gabriel@erau.edu.

Voluntary Participation: Your participation in this study is completely voluntary. You may discontinue your participation at any time without any penalty. Should you wish to discontinue the research at any time, no information collected will be used.

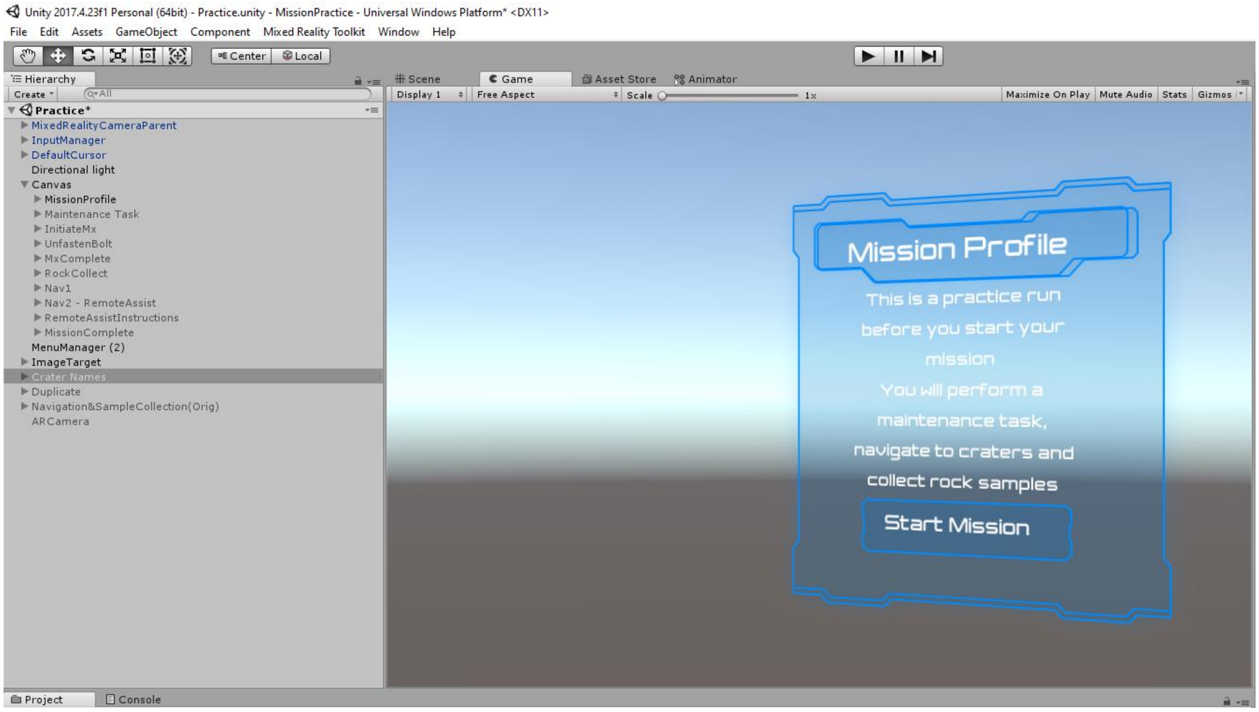
CONSENT. By signing below, I certify that I am 18 years of age or older. I further verify that I understand the information on this form, that the researcher has answered any and all questions I have about this study, and I voluntarily agree to participate in the study.

Signature of Participant______________________________Date: ______________

Printed Name of Participant ______________________________

Appendix D

Unity Programming Setup



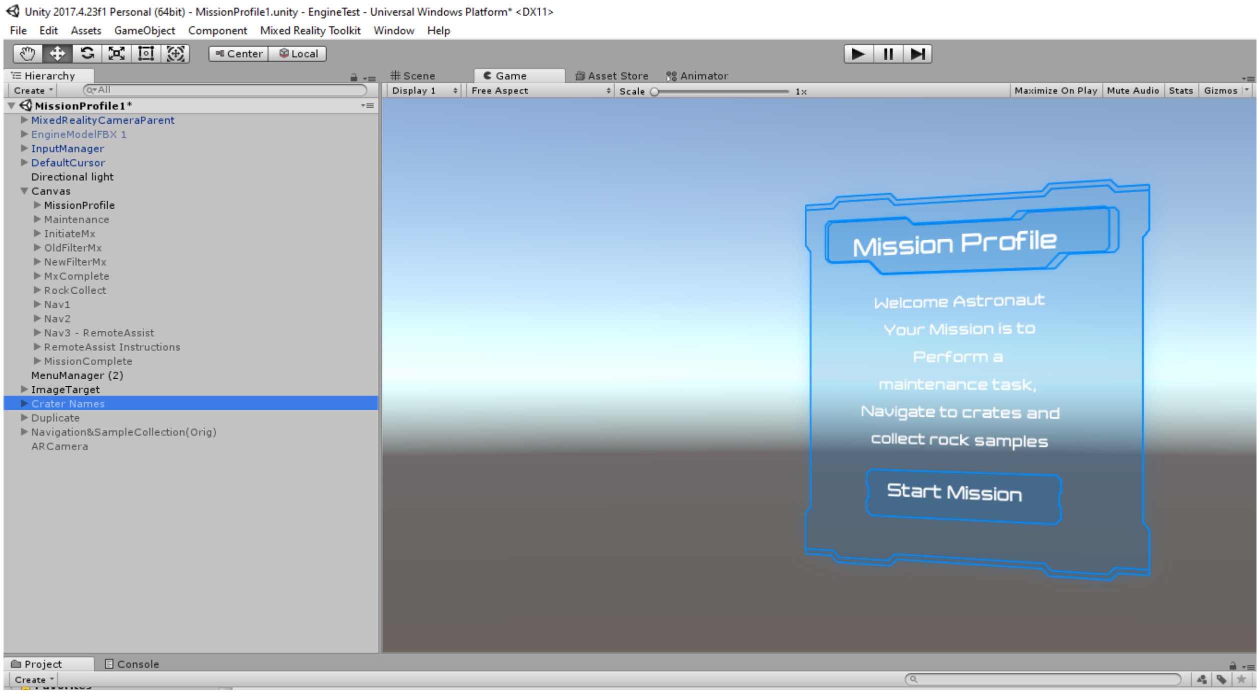
Unity 2017.4.23f1 Personal (64bit) - Practice.unity - MissionPractice - Universal Windows Platform* <DX11>

Mission Profile

This is a practice run before you start your mission

You will perform a maintenance task, navigate to craters and collect rock samples

Start Mission

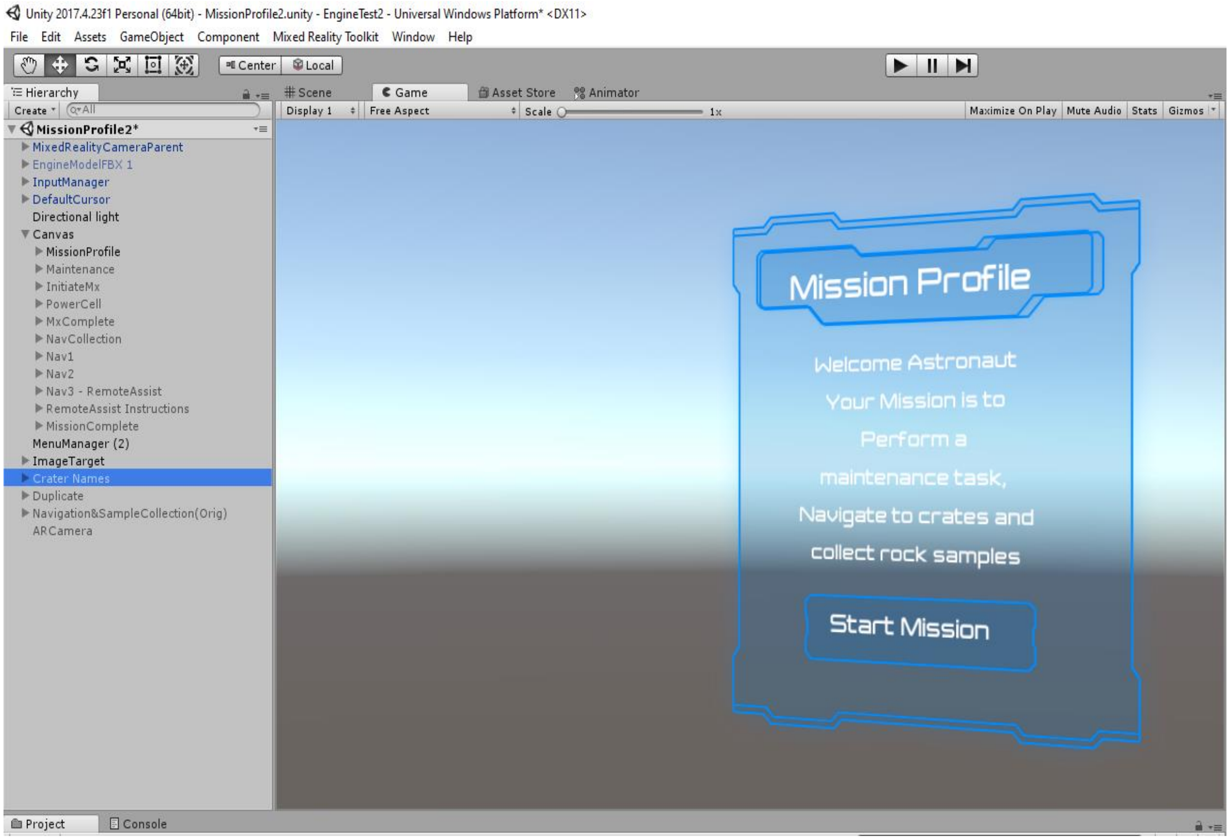


Unity 2017.4.23f1 Personal (64bit) - MissionProfile1.unity - EngineTest - Universal Windows Platform* <DX11>

Mission Profile

Welcome Astronaut
Your Mission is to
Perform a
maintenance task,
Navigate to crates and
collect rock samples

Start Mission



Unity 2017.4.23f1 Personal (64bit) - MissionProfile2.unity - EngineTest2 - Universal Windows Platform* <DX11>

Mission Profile

Welcome Astronaut
Your Mission is to
Perform a
maintenance task,
Navigate to crates and
collect rock samples

Start Mission

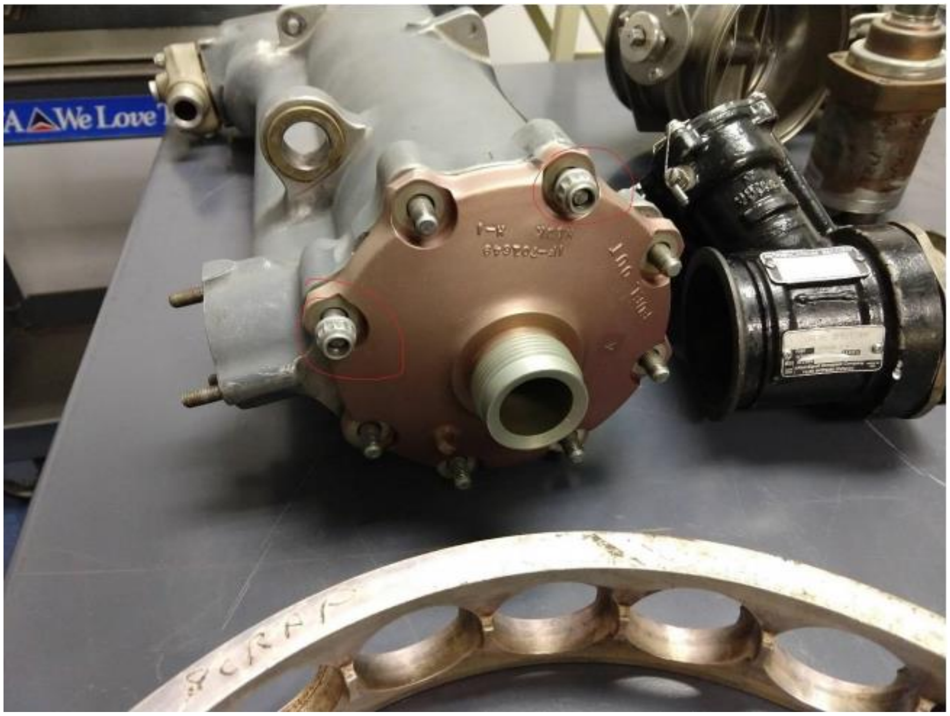
Appendix E

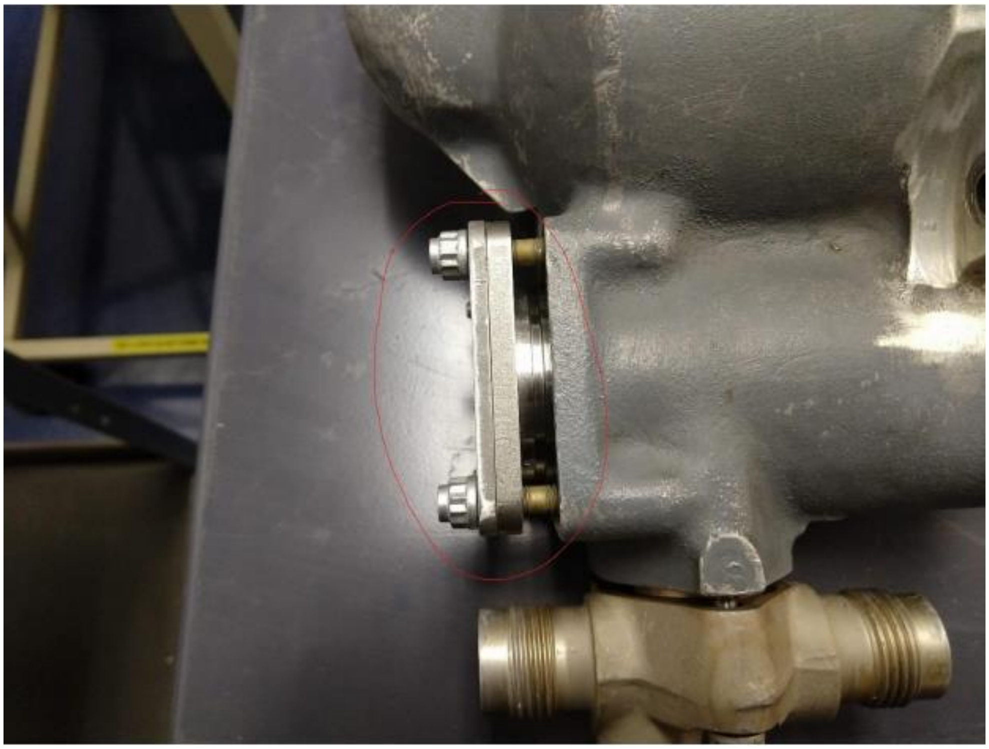
Rock Samples


1
2
3
4
5
6

Appendix F

Mechanical Component





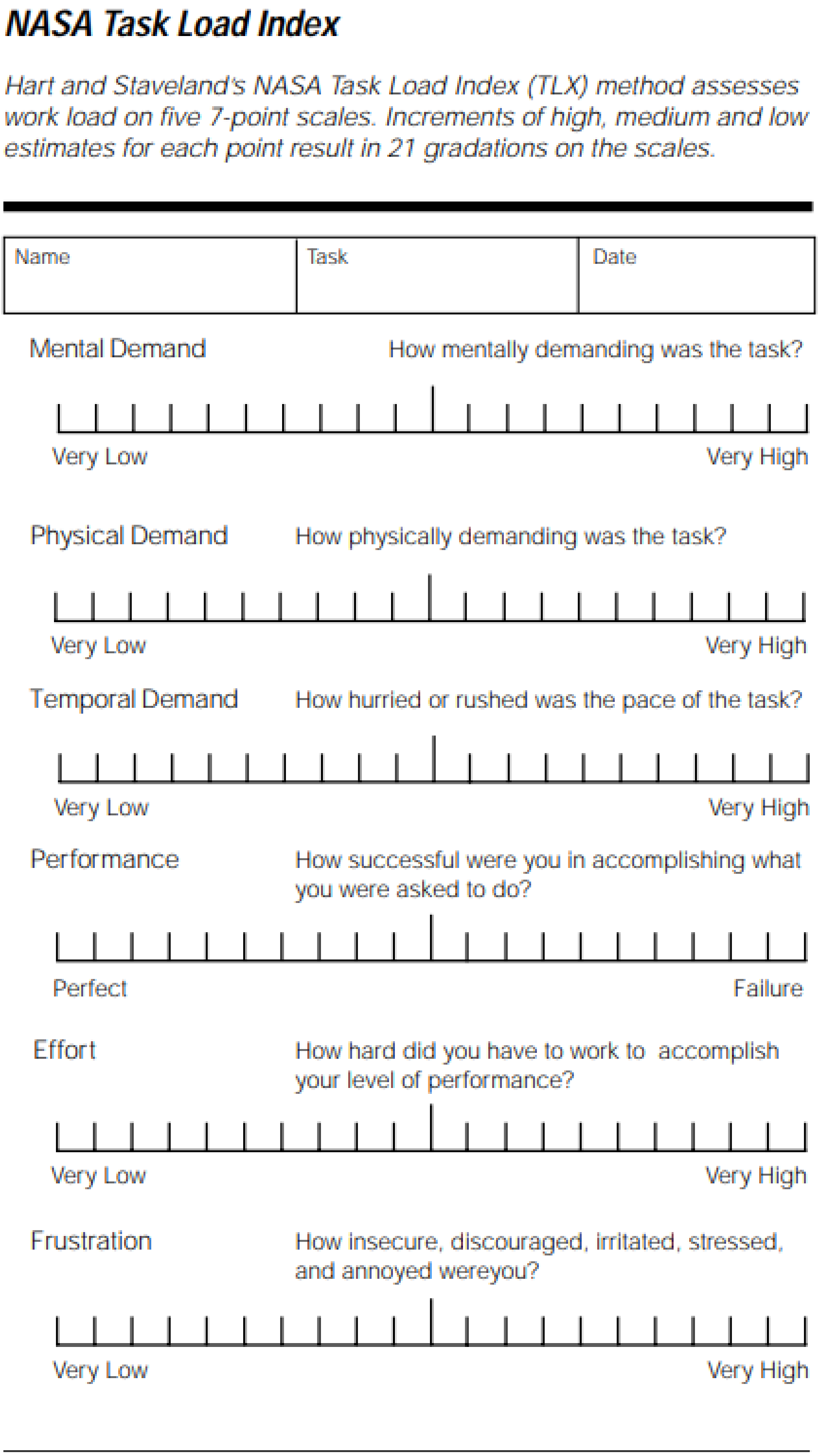
Appendix G

Pre Study Briefing

1) Welcome Participant
2) Describe Study:
    a. Background & Purpose
    b. Room explanation
    c. Astronaut items explanation
    d. Mechanical component explanation
    e. Device explanation
    f. Consent Form
    g. Questions
3) Hololens Tutorial
4) Mission Training
    a. Setup craters
    b. Explain
    c. Video Record
    d. Walk through step by step
    e. Repeat if necessary
    f. NASA-TLX
5) Mission 1
    a. Setup craters
    b. Explain
    c. Video Record
    d. NASA-TLX
6) Mission 2
    a. Setup craters
    b. Explain
    c. Video Record
    d. NASA-TLX
7) Charge Hololens
8) Usability Interview
9) Questions and Pay

Appendix H

NASA-TLX



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

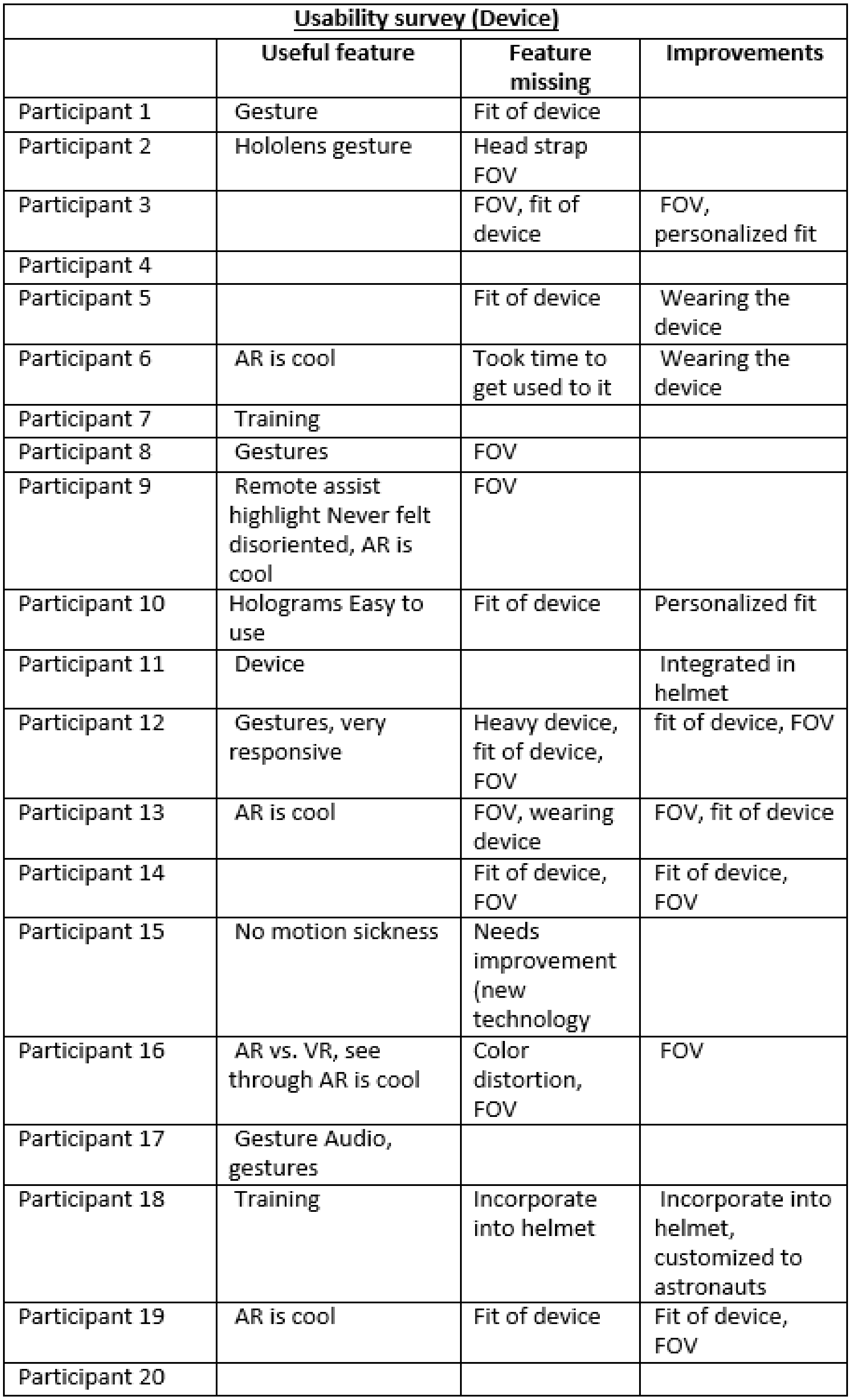
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Appendix I

Participant Usability Interview



Usability survey (Device)

	Useful feature	Feature missing	Improvements
Participant 1	Gesture	Fit of device	
Participant 2	Hololens gesture	Head strap FOV	
Participant 3		FOV, fit of device	FOV, personalized fit
Participant 4			
Participant 5		Fit of device	Wearing the device
Participant 6	AR is cool	Took time to get used to it	Wearing the device
Participant 7	Training		
Participant 8	Gestures	FOV	
Participant 9	Remote assist highlight Never felt disoriented, AR is cool	FOV	
Participant 10	Holograms Easy to use	Fit of device	Personalized fit
Participant 11	Device		Integrated in helmet
Participant 12	Gestures, very responsive	Heavy device, fit of device, FOV	fit of device, FOV
Participant 13	AR is cool	FOV, wearing device	FOV, fit of device
Participant 14		Fit of device, FOV	Fit of device, FOV
Participant 15	No motion sickness	Needs improvement (new technology	
Participant 16	AR vs. VR, see through AR is cool	Color distortion, FOV	FOV
Participant 17	Gesture Audio, gestures		
Participant 18	Training	Incorporate into helmet	Incorporate into helmet, customized to astronauts
Participant 19	AR is cool	Fit of device	Fit of device, FOV
Participant 20			

Participant 21	Overlay clear		
Participant 22		Visibility not the best Distorts color	FOV, color distortion

Usability survey (AR UI)

	Useful feature	Feature missing	Improvements
Participant 1	Checklist usage transitions, cool, easy, clear mx tasks, UI	Lag	Animations , hologram accuracy
Participant 2		Checklist angle	Voice command
Participant 3	Remote assist	Voice command Checklist movement	Instructional videos, more description for rocks, Checklist manipulation
Participant 4	Remote assist	Checklist movement	Voice command to move through tasks
Participant 5	Remote assist	Animations lag	UI improvements
Participant 6	Remote assist Animations	Intervention when difficult task arises	Checklist manipulation
Participant 7	Training Navigation, Remote assist	Animation missing Animations overlay	Checklist manipulation
Participant 8	Checklist Remote assist	Checklist manipulation Lag	Checklist manipulation, Voice command
Participant 9	Remote assist Works well	Cue for next task Animations	Picture description, Point to direction
Participant 10	Holograms Checklist	Checklist manipulation Individual task complete buttons	Checklist manipulation
Participant 11	Checklist, check boxes	Angled menu	Picture description, animations
Participant 12	Checklist very responsive Remote assist, clear sound, clear screen	Task complete button, too close	UI improvements
Participant 13	Holograms Remote assist, checklist		Animations
Participant 14	Remote assist view of AR	Checklist movement	UI improvements