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THESIS

ENABLING COLLABORATION AND VISUALIZATION OF COMPLEX OPERATIONAL TECHNOLOGY COMPUTER NETWORKS WITH AUGMENTED REALITY TECHNOLOGY

by

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December 2018

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13. ABSTRACT (maximum 200 words)

Operational Technology (OT) networks are critical to mission operations on many naval platforms, yet it is often difficult to effectively communicate their status and engage in efficient decision-making at all levels of operation. While the complexity of networks has increased, visualization methods suiting the needs of a diverse set of users have not kept up. To address this problem, this research evaluated whether visualization, provided to a small group of operators acting in a shared work environment on network management, can be supported using commercial off-the-shelf, lightweight, portable augmented reality (AR) technology. The work included building a prototype AR OT network on a U.S. Navy guided missile destroyer (DDG) three-dimensional model with four decks and simulated interconnected ship systems. We then designed and implemented a network infrastructure between a set of Hololenses, and built an application that allowed multiple users to collaborate by viewing the same virtual model in a real-world space setting. A study tested the system interface's usability and its value in network management scenarios. The results suggest that a lightweight AR system, with an interface that supports small-team collaboration, could be a valuable tool for increasing situational awareness in cyberspace and allowing effective team decision-making.

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ENABLING COLLABORATION AND VISUALIZATION OF COMPLEX OPERATIONAL TECHNOLOGY COMPUTER NETWORKS WITH AUGMENTED REALITY TECHNOLOGY

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Operational Technology (OT) networks are critical to mission operations on many naval platforms, yet it is often difficult to effectively communicate their status and engage in efficient decision-making at all levels of operation. While the complexity of networks has increased, visualization methods suiting the needs of a diverse set of users have not kept up. To address this problem, this research evaluated whether visualization, provided to a small group of operators acting in a shared work environment on network management, can be supported using commercial off-the-shelf, lightweight, portable augmented reality (AR) technology. The work included building a prototype AR OT network on a U.S. Navy guided missile destroyer (DDG) three-dimensional model with four decks and simulated interconnected ship systems. We then designed and implemented a network infrastructure between a set of Hololenses, and built an application that allowed multiple users to collaborate by viewing the same virtual model in a real-world space setting. A study tested the system interface's usability and its value in network management scenarios. The results suggest that a lightweight AR system, with an interface that supports small-team collaboration, could be a valuable tool for increasing situational awareness in cyberspace and allowing effective team decision-making.

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
AR	Augmented Reality
ARPANET	Advanced Research Projects Agency Network
ASVAB	Armed Services Vocational Aptitude Battery
COA	Course of Action
CoC	Chain of Command
COMMO	Communications Officer
COTS	Commercial off-the-shelf
CSO	Combat Systems Officer
CPO	Chief Petty Officer
CWO	Chief Warrant Officer
CYBERDORM	Surface Ship Cyber Department Organization and Regulations Manual
DDG	Guided Missile Destroyer
DoD	Department of Defense
DON	Department of the Navy
FOV	Field of View
FPS	Frames per Second
GUI	Graphical User Interface
HMD	Head Mounted Display
HUD	Heads-up Display
ICS	Industrial Control Systems
ICS-CERT	Industrial Control Systems Cyber Emergency Response Team
IDE	Integrated Development Environment
IT	Information Technician
JO	Junior Officer
LDO	Limited Duty Officer
MCS	Machine Control System
MOVES	Modeling Virtual Environments and Simulation

MR	Mixed Reality
NAVSTA	Naval Station
NPS	Naval Postgraduate School
NSWCCD	Naval Sea Systems Command Carderock Division
OT	Operational Technology
PLC	Programmable Logic Controllers
RTU	Remote Terminal Units
SA	Situational Awareness
SCADA	Supervisory Control and Data Acquisition
SSQ	Simulator Sickness Questionnaire
SUS	System Usability Scale
UI	User Interface
USN	United States Navy
VR	Virtual Reality
WDP	Windows Device Portal
XO	Executive Officer

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I. INTRODUCTION

A. RESEARCH DOMAIN

From the dawn of computing, through the entry of networked devices, to the existence of Industrial Control Systems (ICS), visualizing network topologies has become increasingly vital. Early network pioneers did not envision a future requiring multi-dimensional diagrams to illustrate layered firewalls, DMZ sectors, or host-based IPS's. However, in a progressively networked world, becoming fully aware of your physical and logical environment can be vital. Computer Networks require human operators to maintain, repair, and upgrade systems while also diagnosing and fixing hardware or software issues. This network backbone managed by operators is crucial to all operational systems, and the efficient visualization of the network is vital for collaborative troubleshooting and decision-making at all levels of operation. Current network visualization approaches use Two-Dimensional (2D) network diagrams, with logical network mapping, but while the scope, detail, and complexity of networks have significantly increased, visualization methods for them have not. The same basic visualization format created for ARPANET in the late 1960s is still being utilized 50 years later.

In a complex Machine Control System (MCS) environment such as a ship or aircraft, every useable overhead and underfoot space is occupied with a material transfer system. These systems, whether containing liquid, solids, gas, or packetized data, traverse the length of the vessel and do not always take the most expedient or logical route. Physically mapping these lines is infeasible on a single diagram; they are often divided so that each physical compartment is diagrammed on its own separate page. This often results in hundreds of diagrams created for each vessel, which are then hastily combined when large sections need to be analyzed to collaborate on a course of action. This process is cumbersome and distracts network operators and their supervisors from being able to make timely and accurate decisions due to the visual inconvenience of the current models.

B. RESEARCH PROBLEM

Managing resources in an Operational Technology (OT) environment requires full comprehension of every networked node and the connections between them. Without this expert knowledge, managers and their operators run the risk of being at a major disadvantage in an event where a missed detail can bring about disastrous consequences. While the complexity of networks has significantly increased over the past five decades, visualization methods have not kept up; as a result, Situational Awareness (SA) of cybersecurity issues has decreased. Ultimately, current 2D visualizations oversimplify complex OT systems by displaying them as the flat Information Technology (IT) diagrams the networking community is accustomed to seeing, and do not display logical networking elements in the three-dimensional (3D) space that reflects both the physical and logical complexity of these networks. Operators and managers need to view their networks in ways which incorporate both physical and logical views. If a 3D visualization was to take spatial arrangement and position of these elements into account, it would provide operators additional tools to support enhanced collaboration and operational decision-making.

Specific to complex networked vessels, the binder of diagrams created to represent the physical layout of the network is useful for those responsible for a small number of spaces; however, when there are hundreds of spaces, the problem is not just visualizing the network, but managing the required visualization resources. For example, in the event of a crisis such as a collision or massive structural catastrophe, when multiple compartments are devastated, pulling out the relevant network diagrams to troubleshoot connectivity for operational systems is time consuming and error-prone. Collaboratively visualizing these OT networks in Augmented Reality (AR) may provide a sensible solution.

C. RESEARCH QUESTIONS

The following questions have been identified:

- Is it feasible to design and implement an interactive and fully immersive AR network visualization application that supports the tasks of network operators, while using only Commercial Off-The Shelf (COTS) technology?

- What is usability of a fully immersive multiuser Augmented Reality (AR) network visualization application that facilitates network management, operations, training, and support, and serves as a tool for collaboration among the participants from disparate domains?

D. HYPOTHESIS

Our hypothesis is that it is possible to build an AR network visualization tool using COTS technology that further assists operators and managers in their network tasks, cyber SA, and decision-making.

E. SCOPE

This work is limited to the design and development of a prototype visualization of a complex shipboard network infrastructure using COTS equipment. The work also includes a feasibility study (evaluation of the frame rate, latency and other technical parameters) and examination of interface usability using the framework of a formal usability study with human subjects. The AR model and associated scenario is displayed in a head mounted display (HMD) to allow for portability and ease of use. The purpose of this research is to evaluate whether mission objectives exercised by a small group of operators who act in a shared work environment on tasks that concern network management, operations, training, and support, can be supported using Commercial-off-the-shelf (COTS), lightweight, portable AR technology. The study does not include a formal usability study to test the effectiveness of the prototype application against a 2D visualization.

F. METHODOLOGY AND APPROACH

The approach exercised for this study was to first perform a literature review of existing AR applications and procedures, current complex OT network diagrams, and operator-driven network management tasks. Task Analysis was performed by studying relevant information resources, by observing real-time operations at Naval Station (NAVSTA) San Diego. The visualization prototype constructed for this study included the selection of AR as the basis for the hardware and software framework, and it used 3D model of a U.S. guided missile destroyer (DDG) as the foundation for the visualized OT network. Scenarios implemented for usability study originated from the data gathered during Task Analysis. Ultimately a test of the technical aspects of the system was conducted to determine operational feasibility. A formal usability study was conducted using a series of scenario-driven assessments with human subjects. Data from the study and subject observation were analyzed to determine the overall usability of the application in a networked environment. Conclusions were based upon analysis of the data. Future work was identified by collecting all of the ideas and further questions generated as this work progressed.

G. THESIS CONTRIBUTION

The primary contribution of this work is to suggest new tools for achieving improved SA among a group of operators who manage complex multi-layered OT networks, such as those on a USN warship. The ultimate goal of these network tools would be to make their operations timelier and more effective. The application is also envisioned to benefit network managers and their chain-of-command because it provides a whole-picture environment while allowing for a shared-view briefing and more effective communication and problem-solving. A secondary benefit of this research is its support of a variety of domains and situations in which a group of humans needs to engage on tasks which involve complex physical networks such as building electrical grids, water, gas or oil pipelines, and even human anatomical systems.

H. THESIS STRUCTURE

Chapter II discusses past and current uses of VR and AR applications and procedures, as well as OT network visualizations, and operator-based network tasks.

Chapter III depicts how DDG networks are currently visualized, and how the tasks are being completed using these visualizations.

Chapter IV describes how the visualization prototype was built; from the framework decided upon, through the system architecture and Graphical User Interface (GUI), to the scenarios and 3D models used throughout the study.

Chapter V details the usability study from the ground up, and then provides the results gained from the objective, subjective, and behavioral data sets.

Chapter VI outlines conclusions built from this study and provides designs for future work.

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II. BACKGROUND

A. DATA AND NETWORK VISUALIZATION

The utilization of effective data and scientific visualization techniques is essential when creating exact and easy-to-understand network diagrams. Data and scientific visualization although similar, are not identical, and often complement each other in the visual domain.

1. Data Visualization

Data Visualization is a technique employed when creating diagrams that must be easy to understand, but must also include enough pertinent and reliable information to support real-time operations. This technique emphasizes interactive, visual representations of abstract data to strengthen absorption of information by human users [1]. Whomever is using the graphic visualization should be able to interpret and draw conclusions from the contained information set with limited training. As defined, this technique also includes the capability for the visualization to dynamically reflect user movements and interactions. For example, a zoom-in/out feature allows a user to visualize the holistic informational structure, but also permits examination of minutiae to determine data correlations. In addition, a well-designed visualization should be represented in a way that can be understood by both a layman and an expert. Although the layman may not be able to fully understand the data represented, being able to accurately follow the structure and high-level analysis is absolutely critical.

Data Visualization is a subset of Information Visualization and was first envisioned during the 16th century as celestial bodies were being charted by astronomers for land/sea navigation, and cartographers began the daunting task of mapping the earth one landmark at a time [2]. Much like cartographers, network engineers must use Data Visualization techniques to clearly and effectively communicate abstract information onto a medium that allows personnel to dissect, utilize, and dynamically update it. Graphical displays need to show the data, make large data sets coherent, reveal data at several levels of detail, and serve a reasonably clear purpose [3]. Data Visualization was more straightforward when only small parts of the world were available; however, just as in the age of ARPANET with the rapid expansion of network size and complexity, coherent displays of data became much more difficult to develop as complexity rose.

2. Scientific Visualization

Scientific Visualization builds upon Data/Information Visualization techniques by integrating 3D computer graphics into the design. This technique focuses on illustrating datasets created from scientific inquiry, and allows other researchers to understand the problem set, derive insight from the data, and generate logical solutions [4]. There have been many *specific* toolkits created for the broad spectrum of scientific communities utilizing scientific visualization to solve data management problems. These toolkits range from those used in the medical community to present multi-dimensional graphs of disease outbreaks, to those used by the geological community to generate graphic records of seismic activity. While using the same data points as a 2D model, scientific visualization allows more effective manipulation of the model and builds a road toward eventual collaboration toolsets.

The effects of object symbology, color, text font, and resolution are all specific examples of factors taken into consideration when building visualizations in scientific community-specific applications, and wholly effect the usability and success of the model as a diagnostic tool [5]. A model of an isolated object with no background data or supporting information would not be considered a scientific visualization, but the addition of a dataset such as network figures or exact locational data of real-world objects on said model would allow creative adaptation, which is key to innovative problem solving. Properly using Scientific Visualization to represent a network map involves building the model in 3D space, incorporating physical and logical network data, and designing it to be interactable by the community it supports and adjustable as problems change. It is vital to include information and scientific visualization techniques when representing data in multi-dimensional space, and only by applying these techniques to current models will future improvements be possible.

3. Network Mapping: Past, Present, Future

In October of 1969, the ARPANET (Advanced Research Projects Agency Network) was connected to its initial host, and subsequently the first network visualization, or network diagram was constructed. At the time, there were only two nodes, one at Stanford and the other at DARPA, with a link between them that was both uncomplicated and rarely used. As technology progressed, nodes appeared throughout the United States as seen in Figure 1: from Hawaii in the Pacific, to the Pentagon in Washington D.C, to London across the Atlantic.

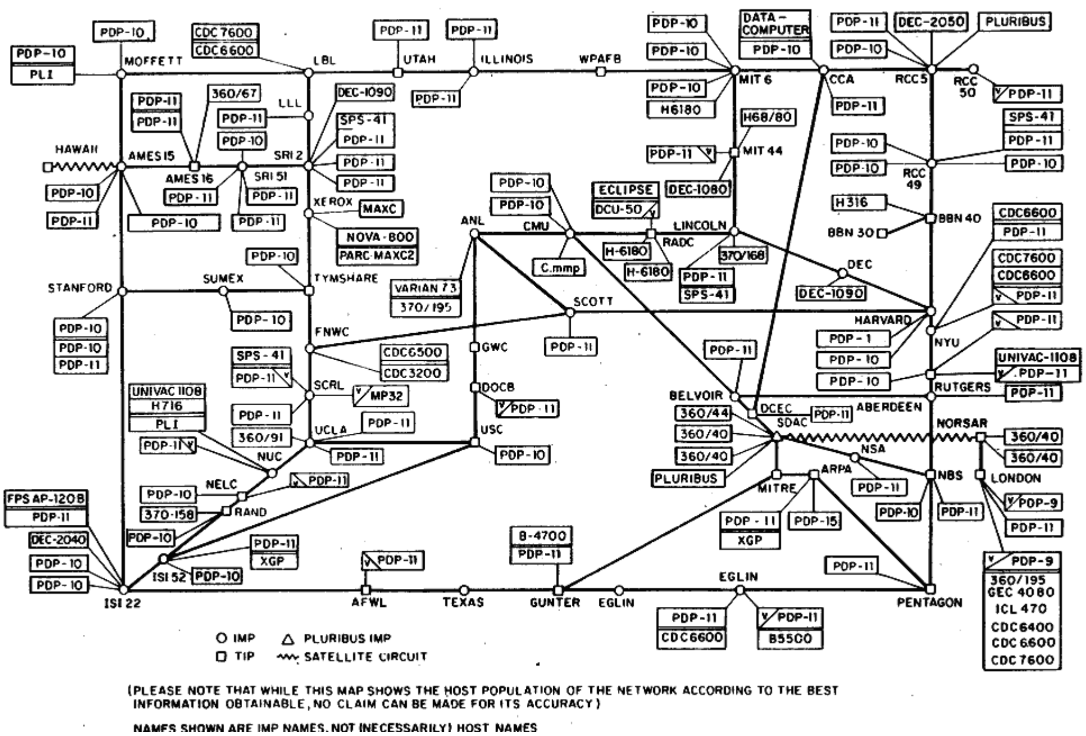

Figure 1. 1977 ARPANET Logical Map. Source: [6].

These nodes and their associated links became more complex, and the routes from one node to another were no longer static. The network engineers supporting the ARPANET required a more precise mapping tool that would allow routing protocols to be developed and analyzed and, subsequently, for standards to be established. In Figure 1, a packet travelling from the uppermost left node, to the uppermost right node would logically traverse the straight path between them; however, if the physical medium connecting these nodes were modified or damaged in any way, the packet would need to travel a different route. Routing tables were created to solve this problem, and network diagrams were upgraded to specify paths taken, and include end hosts on each node. Hosts were continuously added to subnetworks, and physical and logical addressing was accomplished and subsequently added to logical diagrams. Physical space on these diagrams was now at a premium, and visual engineers began removing irrelevant data to make way for more updated information important to building and maintaining the network architecture. Routers held routing information in their memory, and because knowledge of edge devices was no longer needed, "whole internet" network maps became non-vital. Presently, each node in Figure 1 represents a network much more complicated and diverse than the entire ARPANET at its peak. The focus is now shifted to ensuring enough data is included in the diagrams to allow for complete SA of the architecture, but not so much as to overload or confuse the engineers managing the network.

Operating on a network, whether offensively or defensively, requires complete comprehension of every node and connection between interfaces. Without this expert knowledge, the operator runs the risk of being at a major disadvantage in an event where a missed detail can mean a missed opportunity or a new vulnerability. Using the information and scientific visualization techniques listed above, with a standardized structure allows for a reduced a margin of error, while also providing a baseline for successful cyber operations. In the defensive realm, building an accurate network diagram includes first discovering where the edge of an organization's network lies. This includes identifying the gateways in and out of the network, as well as the protocols these gateways use to communicate with entities within the rest of the Internet [7]. Every protocol is handled differently by network devices, and each has its own vulnerabilities and optimal operational parameters. On every occasion in which a network device is added or removed from the architecture, the diagram must be updated, and topology readjusted to make room for the physical state. In a large or complicated network, this happens regularly, and only a well-defined and up-to-date network diagram will allow the vulnerability posture to remain current. Maintaining complete SA in network space is only possible if the network engineer identifies every possible route, every imaginable vulnerability, all verified users on the system, and all traffic flowing through the system. Even with the number of advanced tools at our disposal, this is an impossible task; however, maintaining a systematically updated network diagram can tip the odds in the favor of the network engineer.

The connection of industrial control systems to these already complex networks has further exacerbated the SA problem.

4. Industrial Control Systems (ICS) Network Visualizations

As industrial processes migrated from human controlled devices to automated technologies, Industrial Control Systems (ICS) were pioneered. These systems allow remote monitoring and control by utilizing Programmable Logic Controllers (PLC) and Remote Terminal Units (RTU) on a communication network continually serviced and monitored by network engineers [8]. ICS's began directing smart power grids across the world and are used in most environments where automation is present. Supervisory Control and Data Acquisition (SCADA) control systems are a subset of ICS that are exclusively networked and operate through a Graphical User Interface (GUI) to support monitoring tasks. Terrestrial power plants, offshore oil and gas platforms, and U.S. Naval vessels use machine control systems (MCS) to monitor and regulate various machinery such as pumps, valves, propulsion plants, and even steering control. In addition, shipboard hull, maintenance and engineering (HM&E) systems have been integrated within the ship network to amplify combat effectiveness [9]. As human physical manipulation of these devices was phased out, networking and remote control through various communication protocols was implemented. Early utility systems were based on physical telephone or fiber line mediums, but private independent systems were soon installed using microwave and later satellite communication methods [8]. With these changes came the immediate addition of cybersecurity threats, which led to the later implementation of improved network diagrams and defense mechanisms.

The evolution of ICS networks has largely benefitted complex automated applications, but as communication technologies improved, security standards and process implementation have lagged behind. In 2007 through the AURORA program, the Idaho

National Laboratory proved that it was possible to apply cyber techniques to exploit cyber-physical systems, causing ICS controllers to go out of phase, and irreversibly damage utility equipment [8]. In the U.S., the Department of Homeland Security (DHS) has justified this persistent threat by creating a ICS-CERT (Industrial Control Systems Cyber Emergency Response Team) to "share control systems-related security incidents and mitigation measures" [10]. Internationally, professional certifications for power grids are being instituted, but ICS network visualizations are still using the same network schemes created in the early days of ARPANET. The increasing size and complexity of ICS brings greater risk of physical damage and loss of controlled access. Human factors and space constraints play a larger role in the implementation, operation, and maintenance of their structures and could successfully be represented not just through the physical/logical layer of the system but including the physical details of the surrounding the system as well.

5. Complex Operational Technology Network Visualizations

Current network diagrams of ICS' vary as much as their communication protocols. Many appear to be sophisticated maps of complex networks, with communication lines linking switches, routers, and edge devices. However, the network is located between controlled devices, which could be anything from a rudder for a ship, a water pump in a sprinkler system, or a nuclear centrifuge. These systems are defined as Operational Technology (OT), and are hardware/software that detect or causes a change through the monitoring and control of physical devices, processes and events. Often these OT systems are not logically laid out with a single coax or fiber cable connection but use parallel connections with multiple redundant interfaces. Ultimately, these OT diagrams of ICS systems over-simplify very complex systems to mimic diagrams the IT engineers are accustomed to. However, it is not often possible to fit the data required to conduct real-time, situationally-aware network operations onto these IT-centric diagrams.

Adhering to Data and Scientific Visualization techniques, one way to present the amount of complex data/information contained in these multi-faceted networks would be to produce a graphical representation that includes filterable logical and physical layers, that are also accessible in a natural and accessible 3D domain.

B. AUGMENTED REALITY

1. Augmented Reality vs. Virtual Reality

The most commonly accepted definition of AR was coined by Ron Azuma, who establishes AR as a variation of VR, in that, instead of immersing a user inside a synthetic environment, AR allows the user to see the real world with superimposed virtual objects [11]. Milgram and Kishino define the relationship between AR and VR on the Mixed Reality (MR) spectrum, as shown on Figure 2. They introduced Mixed Reality as the combination of real and virtual worlds, creating a MR continuum that describes the ways in which real and virtual elements can be combined [12]. AR is integrated into the continuum, and as shown, is much closer to the Real Environment than the Virtual.

Figure 2. Mixed Reality Continuum. Source: [12].

AR must have three characteristics: 1. It combines the real and the virtual, 2. It is interactive in real time, 3. It is registered in three dimensions [11]. In essence, AR uses computer-generated models to augment the information coming from the natural world and creates an interactive and immersive experience for the user. The overlaying models or information can build upon the natural world, or mask portions of it, replacing them with user-created visualizations [13]. This process of augmenting the natural world with artificial objects is highly demanding in terms of the processing power required, and currently it is very easy to distinguish these generated graphics from real-world objects. This allows users operating AR technology to view the natural world surrounding them in addition to the graphic visualizations; thus creating the ability to normally interact with other users and maneuver themselves spatially with respect to the visualized object, without fear of losing surrounding awareness.

While VR focuses on creating a virtual environment for the user to absorb and navigate through, AR uses built-in sensor hardware to construct a spatial map of the environment, while placing generated objects throughout this map and consequently on the users visual plane. Much of the technology between VR and AR is the same, such as Head Mounted Displays (HMD), sensory tracking, and use of input devices. However, the VR system can be fully immersive with a wide Field of View (FOV) and as realistic as possible through the use of graphics, In contrast, an AR system does not require immersion, uses a much smaller FOV that is linked to the user's natural FOV, and the graphics need not be as intensive [14]. Further differences are illustrated in Figure 3.

	Virtual Reality Replacing Reality	**Augmented Reality** Augmenting Reality
Scene Generation	requires realistic images	minimal rendering okay
Display Device	fully immersive, wide FOV	non-immersive, small FOV
Tracking and Sensing	low accuracy is okay	high accuracy needed

Figure 3. VR and AR Technology Requirements. Source: [14].

2. Commercial off-the-Shelf (COTS) Augmented Reality Solutions

At the most basic level, AR technology depends on combining graphical representations of assembled 3D models and unaltered real-world scenes on a physical medium that is displayed to the user. As shown in the Figure 4, the user can see the real environment through the optical combiner, but layered into this combiner is the rendered image that the user visualizes in 3D space.

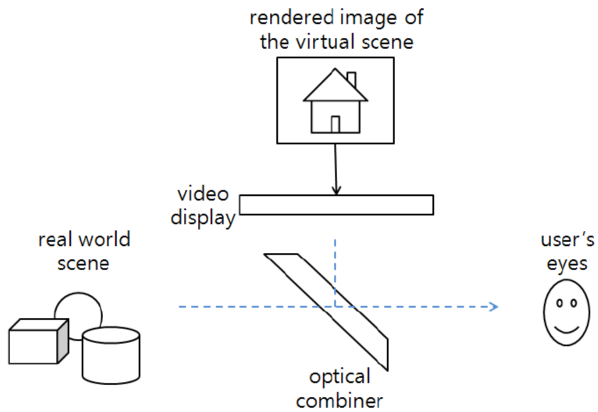

Figure 4. Optical See-through Displays. Source: [14].

Due to the direct view of the real world, the optical see-through display is not limited by resolution, lens distortion, eye displacement, or time delay [14]. However, because the combiner must also include the physical plane the user is working in, the rendered image must be aligned with the real-world scene through a process called registration. As shown in Figure 5, and described in detail by Bimber and Raskar, "Augmented Reality displays are essentially image forming systems that use a set of optical, electronic and mechanical components to generate images somewhere on the optical path in between the observer's eyes and the physical object to be augmented" [15].

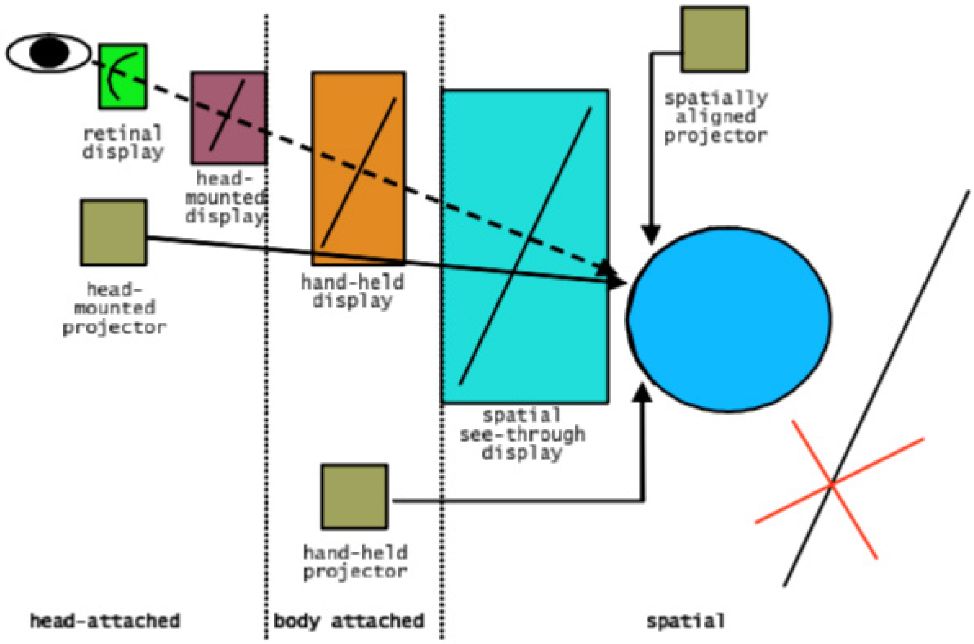

Figure 5. Image Generation for AR displays. Source: [15].

Registration properly aligns the real and virtual worlds with respect to each other, to build the illusion that the two worlds coexist in the same 3D space[11]. Without precise registration accuracy, 3D objects will not be positioned correctly in the real-world, and the visualization through the optical combiner will be inaccurate. Industries using AR to build prototypes or train personnel require this accuracy, and it is a priority for AR system designers to limit registration errors. Registration errors have been defined as being in one of two categories, static or dynamic. Static errors include optical distortion, tracking system inaccuracies, mechanical misalignments, or incorrect viewing patterns, whereas dynamic errors are due to the system lag encountered, or the end-to-end system delay [16]. Much like computing, dynamic registration errors and to a lesser extent static registration errors, are an effect of the sophistication of the AR hardware the visualization is built upon.

a. Hololens

The Microsoft Hololens is the AR system, or mixed reality HMD being used in this thesis, and is displayed in Figure 5.

Figure 6. Microsoft Hololens. Source: [17].

It was engineered for data visualization, training, education, gaming, and design applications [16]. The Hololens uses the basic structure of the optical see-through display but integrates many other components which allow it to be wireless, completely stand-alone, and networkable. These components include a full mainboard which runs a mobile version of Windows 10 and integrates an Intel Atom CPU/GPU as described in Figure 6.

The combiner, illustrated in Figure 4, is also depicted in Figure 7. Figure 8 shows the waveguides with R/G/B layers to display holograms in color, as well as the light engines which project the holographic images to the user through the lenses.

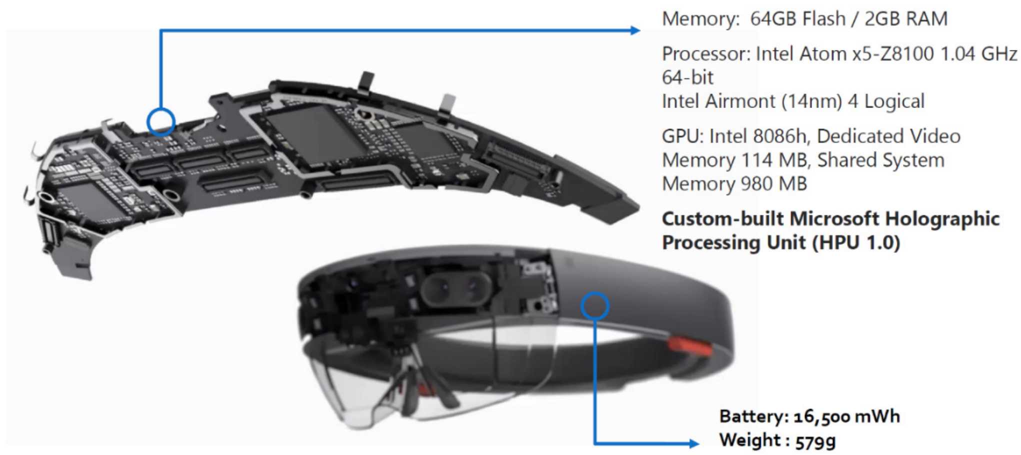

Figure 7. Hololens Waveguide. Source: [18].

Figure 8. Hololens Mainboard. Source: [18].

While there are many AR devices currently in use, the Hololens stands out due to its use of six cameras to build the coordinate graph as seen in Figure 9, which is then utilized to locate the user in physical space, ultimately registering this data in virtual space [17].

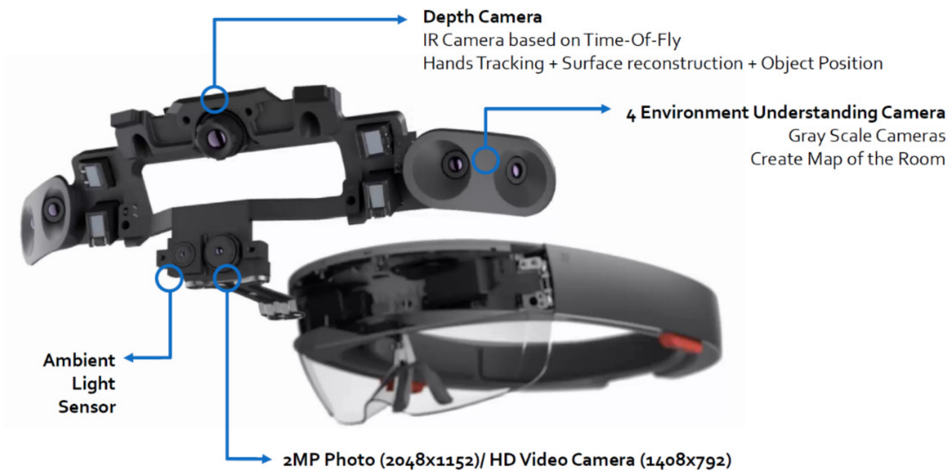

Figure 9. Hololens Optical Sensors. Source: [18] .

3. Augmented Reality Applications

AR is a burgeoning field of study, and, as the hardware supporting the science continues to advance, applications for the use of AR grow exponentially. At this time, there is no AR application that allows collaborative visualization of complex, multi-level network diagrams, but there are many that perform similar visualization tasks.

Using the Hololens, Beitzel et al. developed an application of AR using the Hololens that displays 3D network topologies and navigates through the topology using hand gestures [19]. Their research demonstrated that the use of AR supports human operators and the completion of complex network tasks. They also demonstrated that the Hololens enables physical and virtual objects to exist in the same space, while allowing users to interact with the 3D scene in a way that supports their ultimate objective of understanding the network infrastructure and further supporting increased SA at all levels of network operation. They also demonstrate the extensive Hololens development workflow, which steps through the processes involved when building an application beginning with external datasets, and ultimately ending with an innovative network visualization.

Outside of the networking environment, AR applications have also been used in manufacturing, as seen by GE Aviation's use of Google Glass to evaluate the performance of their mechanics [20], and Boeing's use of the HoloLens to improve wire laying accuracy in their avionic factories by 90% [21]. Maintenance actions have also been determined to be more efficient and precise when instructing via AR in comparison to conducting the maintenance from technical manuals [22]. In the medical field, AR applications are allowing doctors to blend MRI/CT scans with prone patients, allowing: quicker diagnoses; seeing locations for injections and incisions; and display of lifesaving information for first responders. AR technology also provides doctors with the ability to visualize their patients' current bone structure while conducting reconstructive surgery, allowing swift and accurate results [23].

4. Cybersickness and Cognitive Tunneling

The human vestibular system synchronizes with distinct visual cues in addition to the brain to maintain a person's sense of balance, while also "providing information about the movement and orientation of the head in world space" [24]. VR induces distinct visual stimulation, but with current VR HMD technology, the vestibular system is not simultaneously stimulated—the user typically stands still and is not moving, while the visual information presented inside the headset may suggest a movement in virtual environment. This ocular-to-inner ear mismatch often causes symptoms of cybersickness such as increased eye strain, headache, sweating, disorientation, nausea, and even vomiting. Cybersickness is often related to the motion sickness that one could experience in a moving vehicle, or by moving erratically and losing a sense of balance; however, the distinct difference is that the VR users are most often stationary, but feel as if they are continuously moving through "visual imagery" [24].

Cybersickness is considered one of the more important health and safety drawbacks to using any VR device, while also often limiting the time a user can operate while wearing a HMD system. Interactive control of one's virtual environment has shown to be an effective way to alleviate the symptoms of cybersickness [25]. For example, when moving a limb in the real world, the user's virtual limb also moves, albeit with a few milliseconds lag. This allows the user to feel more in control of the simulation and gives the brain cues that visual stimulation is imminent. There are several other factors thought to influence the intensity of cybersickness discomfort, including user freedom of movement, field of view, and graphic lag [25].

All of the current human factor studies of cybersickness associated with the use of HMD’s have been performed using VR devices. An AR device such as the Hololens provides real-world visual cues in addition to virtual hologram placement. In theory, this could potentially provide the brain and vestibular system more synchronous cuing, lessening or even removing the causal influences of cybersickness.

Cognitive tunneling is another health and safety concern frequently associated with AR applications. Normally linked to users who are performing a highly involved/technical task with an associated AR Heads-up Display (HUD), Cognitive Tunneling occurs when the user focuses primarily on the HUD symbology, losing SA and resulting in decreased performance in tasks that require real-world event data [26]. Cognitive Tunneling is a large concern to AR users in the automobile and aviation worlds when their helmets with built-in HUD’s become the focus for the user, because the high-speed environment becomes much more threatening without the required SA. AR application developers must take Cognitive Tunneling into consideration when building their apps, to ensure that the HUDs do not become the main focus for the user, and real-world events are missed in the external scene [26] .

C. SITUATIONAL AWARENESS

1. Situational Awareness Concept

Although many consider this to be the information age, is has also been coined the misinformation age due to the amount of erroneous or misleading data being consumed by users at all levels of operation. Filtering out the valuable and usable from useless or potentially erroneous data in a timely manner, while organizing the information in a meaningful way, can be challenging at times. Even working with completely reliable data from a trusted source, the massive amount of information produced must be parsed, combined with other meaningful data, and presented in an optimal form to create a useful end-product for the user. Conversion of raw data into information may be initially performed by a computer system, but for a range of tasks, the final result of data processing is ultimately ‘consumed’ by the human eye and brain. Human perception and cognition are imperfect and require differing amounts of information and different types of data representation in order to be used in timely manner. “The body of available data will need to be processed and interpreted slightly differently by different individuals, each of whom has varied and dynamically changing but inter-related information needs…what is truly information is largely in the eyes of the beholder” [27].

Situational awareness (SA) is formally defined as “human perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” [27]. Simply put, SA means that the individual understands which events currently transpiring around him are significant, and which are not. SA does not just stop at this this point, however: the information deemed significant is then used to make informed and timely decisions. Endsley created a model shown in Figure 10 below that depicts SA as a main precursor to effective decision-making [28].

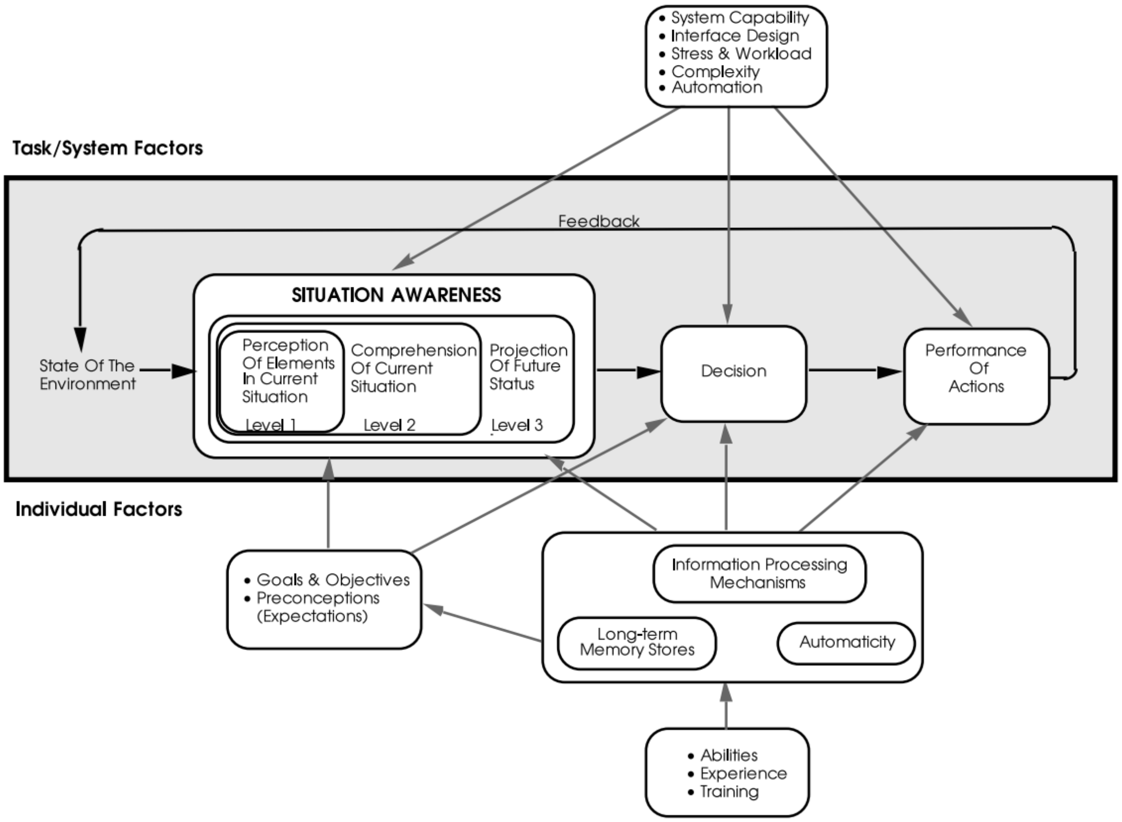

Figure 10. SA in Dynamic Decision-Making. Source: [28]

2. Situational Awareness during Cyber Operations

The growing complexity of cyber systems has pushed SA to the forefront of the minds of developers when building user interfaces (UI) designed to translate bits of data into useful information. The information presented is processed by a cyber operator, who ultimately makes a decision during a time-sensitive situation. Determining what aspects of the situation are important for an individual operator's SA is normally approached using goal-directed task analysis [27]. The information required to make an informed and timely decision is identified during this step, and software purpose-built to make decision-making simple and effective is developed.

A subcategory of SA, cyber SA is defined as "the concept of understanding and visualizing the networked environment and its individual elements to identify changes across time" [29]. Even with the number of effective tools at our disposal, this complete

SA in the current data overloaded era is impossible to reach. Operators can only do their best to mitigate losses of SA by maintaining a systematically updated network diagram and knowledge of the associated information flow into their system.

Building an accurate network diagram includes first discovering where the edge of the network lies. This includes identifying the gateways in and out of the network, as well as the protocols these gateways use to communicate with the rest of the Internet [7]. Every protocol is handled differently by network devices; each has unique vulnerabilities and operational tendencies. Every time a network device is added or removed from the architecture, the diagram must be updated, and the topology readjusted for the differing physical and logical states. In a large or complicated network this occurs regularly, and only a well-defined and updated network diagram allows the vulnerability posture to remain unchanged and cyber SA to be maximized. A specially designed network SA GUI could be a tool that provides effective network data manipulation and reduces cognitive load. Thus it would better empower human operators and help reduce human errors

D. MULTI-USER COLLABORATIVE ENVIRONMENTS

Collaboration is defined as a situation when two or more people work together to complete a task, or achieve a goal [30]. Humans are social beings, and collaboration has often been used to divide work and accomplish a shared outcome with mutually beneficial results. The advent of telephone and computer networks permitted the term to be applied not only to face-to-face interactions, but also to remote collaboration with individuals who may be thousands of miles apart. As virtual and augmented reality systems entered the market, the possibility of visualizing a task by the means of real time, interactive computer graphics, and collaborating in a shared task has emerged.

1. Face-to-Face Collaboration via AR

One of the early conceptual models demonstrating the utility of multiple humans collaborating on a shared medium was "Studierstube." This work demonstrated an architecture of multi-user AR collaboration, and concluded that the system provided a "natural working atmosphere" combining computer generated information with natural communication channels [31]. The Studierstube study also identified six properties of collaborative AR:

- *Virtuality*: A user can view/examine objects not-accessible/non-existent in the real world.
- *Augmentation*: Real objects can be augmented with spatially aligned information, such as descriptions or guidance.
- *Multi-user support*: Multiple users work together to discuss, design, or perform joint work. Normal human interactions are richer than computer-governed interaction.
- *Independence*: Individual users have the option to move freely/ independently of other users.
- *Individuality*: Displayed data can appear in different form for individual viewers depending on their personal needs and interests.
- *Interaction/Interactivity*: Visualized data can be explored interactively and may be kept private or shared with other users on the system.

Soon thereafter, an AR prototype where users share a physical game field and a puck to play air-hockey was introduced [32]. This research concluded that the AR system provided much higher user interactivity, and a more natural play-style than a totally immersive VR application.

2. Remote Collaboration via AR

Remote collaboration allows users to visualize a problem, a set of information, or a graphic model from two physically different locations but within the same virtual space. This concept removes the inherent limitations of being in two separate geographic locations and creates a near-natural communication medium. In 1998, Billinghurst created an AR teleconferencing application, which showed real-time video of two users communicating on a life-size virtual video. These videos appeared projected into each users real-world space [33]. In comparison to VR, the users in the AR application felt that the other users were more "present" than in traditional AV teleconferencing, and that "it was easier to perceive one another's nonverbal communication cues" [34]. Presence is very important in collaboration because audio/physical cues are heavily tied to how 'real' a user feels a collaborator or remote user is. These cues allow more efficient collaboration and/or problem solving.

3. Social Presence (Co-presence)

Social presence is the sense of "being together with another, including primitive responses to social cues, simulations of other minds, and automatically generated models of the intentionality of others" [35]. The physical or simulated presence of persons in a collaborative environment can differ widely. In a real-world face-to-face collaborative environment, all collaborators are physically located next to one another and can naturally perceive social cues, such as the frowning of a brow, a nervous tick, leaning of the body, or questioning glance. Each of these audio and visual cues is interpreted by the rest of the group, and they affect their further actions within the environment. In an environment that supports remote collaboration, the users cannot physically see any other user and must ingest (receive) visual information that depicts their remote, collaborative partners. When engaged in face-to-face collaboration via AR, users are able to see real-world physical cues (this, of course, includes the ability to see co-located collaborators), and can also seamlessly visualize virtual objects in their shared space.

Whether the user is physically located with other collaborators, or is part of a virtual simulation, each scenario will differ in its amount of perceived social presence. Social presence is an important part of multi-user collaboration and contributes to how well a group of users can work together by minimizing perceived physical distance. Although not empirically proven to be applicable to all collaborative situations, it would not be surprising to find situations where there is a direct relationship between perceived social presence and the effectiveness of the collaboration.

III. TASK ANALYSIS

A. INTRODUCTION

Prior to offering a tool to aid a human task, one must understand the task. This includes, but is not limited to, obtaining information about current users, the environment and conditions under which a human user performs the task, where and how the task is currently being completed (actions and procedures), tools that are used, collaboration and communication with other humans that happen during the task execution, human performance that needs to be supported, including the criteria for successful task completion. By understanding these areas, the development of novel technical aids can be well scoped and does not overreach or underperform with respect to the requirements of the supported task. A way to do this is through Task Analysis. It was defined by Kirwan and Ainsworth as "the study of what an operator (or team of operators) is required to do, in terms of actions and/or cognitive process, to achieve a system goal. It provides the user with a blueprint of human involvement in a system" [36]. Task analysis can be used at any point in the design cycle, while testing the prototype system, or when measures of success are determined during the evaluation of the application.

OT networks are, in general, more complex than IT networks, which are singly focused on providing data to and from interfaces. This is especially the case on naval vessels, which depend on OT networks to run propulsion plants, desalination plants, safely navigate, or even fire their guns. The importance of these networks in effect magnifies the responsibility for those who manage them and reveals why correctly visualizing them is important. In the United States Navy (USN), the Commanding Officer (CO) is held responsible for these networks, but the sailors conduct the daily technical tasks on the network. When there is a situation with the network, or any of the networks' supported systems, that requires command guidance, the sailors must provide detailed information to their superiors, which is then briefed up the Chain of Command (CoC) to the CO. This brief is often based on highly technical material; however, as it progresses up the CoC, it is simplified, but still must provide a detail-oriented visualization to enable effective decision-making by the CO. This chapter will discuss the current network SA tasks, users involved in these tasks, and how success is measured after the task is completed.

B. EXISTING NETWORK SA TASKS AND PRACTICES

Day-to-day network operations onboard a naval vessel, are focused on ensuring connectivity of supported systems, and providing timely reports of outages or attacks that would compromise the network's integrity. These reports provide cyber SA for the CO and are important onboard due to the interconnectivity between shipboard systems. If these systems are adversely affected, the CO may be required to employ weapons or prepare tactical maneuvers differently. The fragility of the network infrastructure to what may appear to be small changes can drastically affect the ability of the ship to operate in contested environments and stresses the importance of precise and easily understood network visualizations. The task of briefing pertinent network information to the CoC in the case of an adverse event is not formalized in any kind of manual, but is a learned skill. Such briefings will differ depending on many factors, including but not limited to: the severity of the event, operational necessity, the size of the command, and the personality of the CO. However, there are enough similarities among briefing cases, that it is possible to present a general description of that task sufficient for developing success-enabling tools.

1. Team Forming and Collaboration

In the case of a scheduled/unscheduled network outage, or any sort of malicious attack on the ship, the first responder will most likely be a Navy Information System Technician (IT); i.e., an Enlisted sailor who is responsible for network administration, in addition to many other IT-related tasks throughout the ship. This sailor will be on the bottom of the CoC, and is usually the most technically knowledgeable. This individual understands the basic components and can make repairs to the network or related systems, if required. His primary role in this task is to bring the network issue to the attention of a sailor higher up in the CoC, someone who has a more administrative role, but who also understands the technical aspects of the issue. Together, they will bring the issue up with their supervisor, and at this point, collaboration begins. These sailors will work together in a freeform conversation and determine the consequences of the network issue on the OT systems onboard; this work will include generating advice regarding the Course of Action’s (COA) that can be taken to modify the network and mitigate the significance of the problem.

Some of the factors the IT’s and their supervisors will take into consideration when making these COA’s include:

- Current tactical situation
- Current status of the network
- Current status of inter-connected ship systems
- Systems which would need to be made unavailable for operational use to mitigate the issue
- Length of time each system would be unavailable for operational use to mitigate the issue
- Technical expertise required to make necessary changes in the network and connected systems to mitigate the issue
- Advice from individuals who have necessary expertise to execute requested changes
- Availability of correct tools and hardware to make the necessary changes to ship systems/network architecture

This collaborative discussion depends both upon the expert knowledge of the participating sailors, and upon a series of network diagrams that allow them to map the issue and plan appropriate COA’s. The diagrams used by the collaborating parties are for individual ship compartments, so if multiple compartments or even multiple decks are involved in the outage, the team could be utilizing anywhere from 2–30 individual sheets of paper during their discussions. The hard-copy diagrams often lead to confusion and inevitable mistakes during time-sensitive events, and are also cumbersome to move around and display effectively to the group of collaborators. Once the COA's have been established by the network administrators and their immediate supervisors, they bring their plan to the CO, who makes the final decision. As described in the U.S. Surface Ship Cyber Department Organization and Regulations Manual (CYBERDORM), the CO is responsible for "the defense of the cyber domain of the ship. COs will use all available means to understand and establish the cyber posture for the ship" [37]. The brief given to the CO by the network administrators must account for the fact that he/she may not fully understand the network architecture to the extent that the IT's and administrators do, so it is vital to convey the effects the COA's will have on ship system functions to establish overall SA, and not get bogged down in the details. Once the CO has been briefed, they will take all factors into consideration, and make a decision that is best for the safety of the ship and crew.

2. User characteristics

Beginning at the bottom of the CoC, the first users working the task are USN ITs, whose ages range from 18–30, must have a high school diploma, and must have an Armed Services Vocational Aptitude Battery (ASVAB) minimum score of 222 [38]. A score of 222 puts the sailors in the top 32% of applicant as the chart at [40] shows and is a relatively selective USN rate. The IT's have diverse backgrounds and come from throughout the U.S. They are required to be U.S. citizens, but are not required to be birthright citizens. After bootcamp, and once selected to be an IT, they go to A-School, and are given orders to their first shore(land)-based or sea-based command. These sailors will be operational for a couple of subsequent commands before C-School, which further broadens and deepens their network and communication education. Physically, all sailors have to pass a Physical Fitness Assessment every year, which ensures they can perform to military standards. In addition, all sea-based sailors must pass an operational screening which will filter out sailors with any sort of extensive injury or illness that would affect them during normal operations. The most senior IT is normally a Chief Petty Officer (CPO), a sailor who has been in their specific job for anywhere between 10–30 years, and both understands the technical specifics of the network and can bridge the communications gap between administration and operational management.

Following the ITs in the CoC is their supervisor who is a Junior Officer (JO), Chief Warrant Officer (CWO), or Limited Duty Officer (LDO). These officers can range in age from 23–40, and have as little as one year or as many as 30 years in the Navy. All officers have an undergraduate education, but not all have obtained a technical degree that allows them to understand the mechanics of network management. In addition, they are on other ship watch rotations, and will not spend more than a couple of hours each day in the network spaces. Hence, they will trust that the senior ITs will keep them abreast of any problematic network issue. The officer in charge of network management is designated the COMMO (Communications Officer), and has overall responsibility for the network. The COMMO reports to the Combat Systems Officer (CSO), who reports directly to the Executive Officer (XO) and to the CO.

The XO/CO are at the very top of the CoC onboard a naval vessel and are given responsibility over the entire ship. Both have been in the Navy for a minimum of 10 years in the case of commanding a patrol craft or minesweeper, to over 30 years for command of an aircraft carrier. Both the XO and CO have a minimum of a master's degree and may even hold a doctorate. They have had multiple tours on anywhere from 2–10 different ships and have accumulated a vast amount of operational experience to bring to bear in any situation. However, neither the CO or XO necessarily have expert knowledge of their networks. In view of that, each still requires a detailed brief using a form of network visualization that explains where/what systems are being affected, and what the COA's will be to bring them back online.

From the IT operator, through his supervisor and the COMMO, to the CSO and CO/XO, all members of the group must work cooperatively to successfully accomplish the task. Although often broken up into 2–3 successive sub-tasks, each iteration provides the next task with better SA, and a resulting decision that is much more informed.

3. Operational Environment and Conditions

This network SA task takes place on all USN vessels, on an as-needed basis, but could occur as frequently as a daily in some operational situations. From the time of installation of the network and its connected systems, to the time they are removed, these network tasks are required in an attempt to ensure there are no unforeseen consequences from actions taken on the network by any user in the CoC. Operationally, the USN vessel conducting these tasks could be in port or underway; in either case, the task would be nearly identical.

4. Success criteria

Success requires that the COAs for this network SA task need to be built from the ground up. Utilizing the expertise of the ITs, and the operational and tactical expertise of the officers onboard, the objective is to accomplish the task effectively and efficiently. COAs must be succinctly briefed to the CO, and CO needs to understand them fully to make an informed decision. The COA brief needs to be visually simple enough so that a cognitive overload is avoided and so that the CO can quickly comprehend of the salient information, thus allowing a quick decision to be made. This will ensure the network issue is appropriately mitigated and allows ship systems to be promptly restored to fully operational status.

The following are assumptions we are making as we go forward with our system, and list what we believe should be taken into consideration as criteria for success in the task:

- There should be good communication between collaborating users (team members) as well as up the CoC during multi-user briefings.
- ITs must be able to communicate information to their superiors in a meaningful and efficient way.
- ITs must be able to understand network visualization symbology and know how to explain a complicated diagram to personnel not familiar with network architectures.
- All users should have some basic level of technical knowledge of the networks and connected systems.

- IT's must have network SA and be able to integrate it into briefs to add upon operational expertise of the officers in the CoC.

- Officers should have operational SA to build upon the COA brief being presented to the CO/XO as well as manage risks associated with manipulating OT network.

C. CHAPTER SUMMARY

The network task described throughout this chapter has become steadily more complex as an integrated OT network is now part of nearly every onboard ship system. By detailing the task in its entirety, listing the user characteristics, operational environment and conditions, and the success criteria, we have established requirements for an application framework that has the potential to efficiently support accomplishment of the network task to a superior standard.

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IV. PROTOTYPE SYSTEM

A. INTRODUCTION

This chapter presents the motivation for using an Augmented Reality device to prototype a novel form of network visualization and enable operators and decision-makers to maintain maximum Cyber SA in a complex and contested network environment. The chapter will discuss the full design process that was undertaken and include solutions to issues brought up during the task analysis. The principal goal of this prototype was to allow users the freedom to walk around their restricted space and visualize a complex network. The same solution could then be used to expand network knowledge for a single person or be deployed by a group of users as a teaching or Cyber SA briefing too1. While building the application, our continuing requirement was the physical space needed to operate in, power to charge the device, and a wireless network capable of simple relayed broadcast messages. Updating the network in the case of added nodes or ship systems requires a new software build using a desktop or laptop, but the Hololens system could then be disconnected and taken wherever required. It is reasonable to expect that the users of this system would have easy access to a computer/laptop capable of the build, and therefore, future users with sufficient training could make changes and deploy this tool.

B. FRAMEWORK

1. Why Augmented Reality?

As put forth in Chapter II, AR and VR are two ends of the Mixed Reality spectrum, and a task's objective will dictate which one will be chosen for a specific task. The main motives behind choosing AR device for our research included: high mobility of the viewing device (Hololens), its self-contained nature, and, being an optical see-through AR device, allowing team members to clearly see each other in while collaborating inside the shared physical space.

The Hololens is a completely self-contained solution—it has the entire processing and optical see-through display system enclosed in the headgear, which allows completely free movement around the workspace. This mobility is important in any sort of collaborative work environment, but even more so on a military vessel that prioritizes space for ship systems, and not provide many conference rooms or open spaces. In essence, the Hololens AR system supports operation even in small spaces, while not requiring any other apparatus which would restrain user's movement in the space.

Having an unobstructed collaboration between the team members was a large motivation behind this prototype, and the ability to see one another during discussions or briefs was of great importance. Immersive VR does not allow this sort of communication—that technology assumes that the entire set of visual information presented to the users is simulated and the visual information coming from the real world is shut off. There are quite a few collaborative applications in the VR environment, but they all involve the use of avatars—the animated figures that represent the users. This sort of communication would not work in a professional environment, and especially not while briefing or providing information through a military CoC. Also, safety risks in a constantly moving and changing environment such as an underway vessel are evident – being able to move and grab a table for support in the case of a large swell or course change is an absolute necessity there. Immersive VR would not be able to provide this to the users, who would be required to either remove the VR headset, or blindly grab the nearest structure for support. The team members could use a desktop solution (desktop VR) instead, however that would force them to look at the screens and not at each other, and as a result lose the ability to engage in face-to-face communication.

2. Why Microsoft Hololens(vs. Google Glass/Meta 2/Magic Leap)?

After concluding that AR technology was the best method to visualize network diagrams and support seamless communication in a collaborative environment, we selected the Hololens because at the time, it was the only self-contained, wireless device capable of processing the graphics and network messages required for the prototype. Google Glass was wireless, however that display solution was monocular, did not have the necessary processing power and no visual FOV of required size to project binocular images with necessary complexity to support the network tasks. Meta 2 looked promising as an AR device, but it was not completely wireless, and there were very few development or networking toolkits available at the time of its release. Magic Leap was the last device that would have fit all of our requirements, but it was not released until Sep 2018, nearly a year after we began development. The Microsoft Hololens was sufficiently user friendly, and there were already developers who had begun building applications and sharing their successes. The on-board depth cameras, CPU/GPU processing power, and network card supported all of research requisites, and the Universal Windows Platform (UWP) simplified application support, logging, and Microsoft Windows integration. In summary, the Hololens was the ultimate solution to our prototype requirements and allowed us to meet our research goals.

3. Development Environment

(1) Unity

Unity was selected as the main development platform and game engine. This selection was based on the level of Hololens support provided by the Unity Development team, and the presence of multiple networking and graphics toolkits designed to set the stage for collaborative application development. Additionally, the Unity asset store supplied nearly all of the graphics for the UI buttons, UI text, canvases, and HUD controls, which allowed us to invest development time on project-specific issues. There was no requirement for any of the features included with the Professional license, so the Personal version of Unity was used throughout this research effort.

(2) Blender

Blender is a free and open-source 3D modeling application that was used in this project to build the OT network, ship compartments, and networking objects on the model of the DDG, and integrate them into the scenarios of the usability study.

(3) Microsoft Visual Studio

Microsoft Visual Studio was the Integrated Development Environment (IDE) used to develop the application, as well as debug, build, and deploy it across the Hololenses. The deployment process was especially supportive of the Hololens thanks to UWP compatibility, and the ability to batch deploy the application to all Hololenses simultaneously.

4. Collaborative Networking Solution

The evaluation and analysis of the network task in Chapter III uncovered that the collaborative element is a significant and integral requirement for task success. The Hololens does not natively collaborate or share data between networked devices, but the tools to enable collaboration are available through the Mixed Reality Toolkit developed by Microsoft [41]. In addition to providing the basic networking framework to broadcast packets, the toolkit is a rich source of scripts, components, and assets included for the purpose of accelerating application development. The toolkit GitHub repository mentions that the aim is to “reduce barriers to entry to create mixed reality applications and contribute back to the community” [39].

Also known as the Hololens *Shared Experience*, projected holograms are not just created for a single user—the applications can share spatial anchors between Hololenses, allowing users to “render a hologram at the same place in the real world across multiple devices” [40]. Sharing the world anchors between Hololenses creates a space that is common for all users, making briefing and teaching much more intuitive.

5. Required Hardware

To develop the wireless prototype and network backbone, the following hardware was utilized:

- 5x Microsoft Hololens devices and included clickers
- Alienware 17, 8th Generation Intel® Core™ i7-8750H, 32GB RAM, GTX 1080Ti Laptop
- TP-Link N750 Wireless Router

C. SYSTEM ARCHITECTURE AND DEVELOPMENT

The prototype system architecture as visualized in Figure 11 contains four Hololenses and their Bluetooth clickers, a router, and a laptop, all connected through a wireless access point created by the TP-Link router. The sharing service hosted on the laptop creates a logical network infrastructure which enables holographic collaboration between devices. The Hololens' wireless capability allows users to travel anywhere within the immediate space and continue to communicate effectively. The TP-Link router creates an access point to permit the Hololenses to broadcast custom packets to one another through the sharing service.

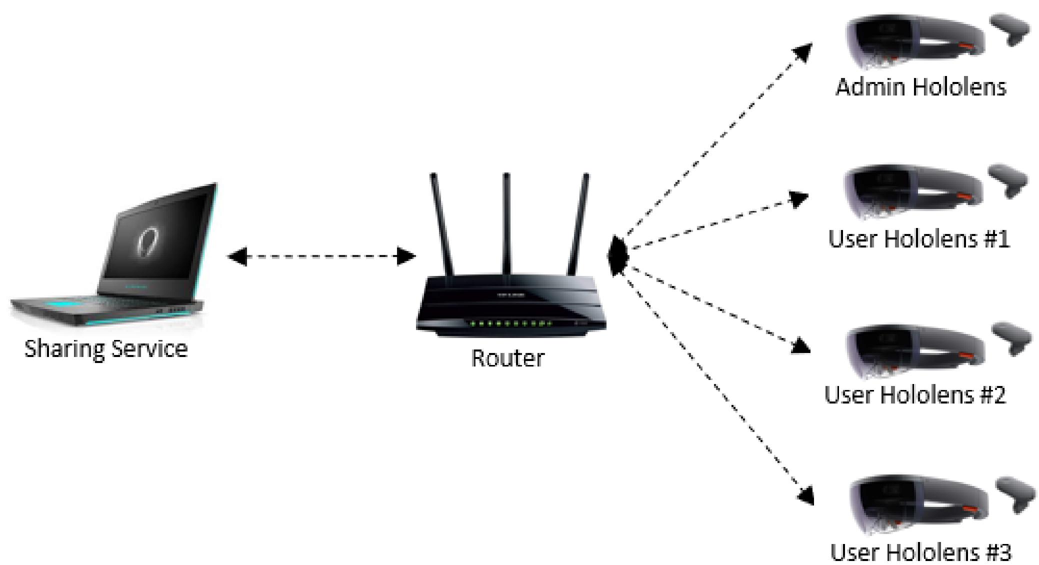


Figure 11. Prototype Architecture

All Hololenses are deployed with identical OS and application versions. The prototype application is built on each Hololens, and although shown here as a specific device, the admin Hololens is not required—it was used in that function only during the Usability Study as a control (which will be discussed in Chapter VI). Each Hololens device had a clicker, which was very useful input device in case an application required a lot of user interactions with the 3D model. For the user, continuously using the arm stretched out above the waist, is tiring and it may result in a physical pain; being able to keep the hand relaxed at one's side while using the clicker to interact with the 3D objects avoided user fatigue.

D. SYNTHETIC ENVIRONMENT

1. Audio/Voice Controls

The Hololens has the ability to recognize and be controlled by voice or audio cues, as well as output sound in response to environmental or user-created prompting. However, for this prototype we determined that using voice commands would not support collaborative decision-making and decided against enable these features. In the future, if the user wanted to use voice commands instead of (or in addition to) the included HUD menu, it would be inconsequential to enable these audio features, and rebuild the application.

2. Gestures/Clicker

In addition to voice commands, Hololens has two core component gestures that form the foundation for possible user actions (hand gestures), Air Tap and Bloom. As the name suggests, Air Tap is a gesture that emulates a user tapping, as seen in Figure 12, with an action much like a mouse click. Once a user gazes at an interactable object and air taps it, the system provides coded feedback. This could be anything from a basic object selection, manipulation like rotation, or translation of the entire simulated scene. The Bluetooth clicker, which is a standard with the Hololens accessory, executes the same action as the Air Tap, but is much quicker to register on the Hololens, and does not require the user's arm be in view of the Hololens' cameras.

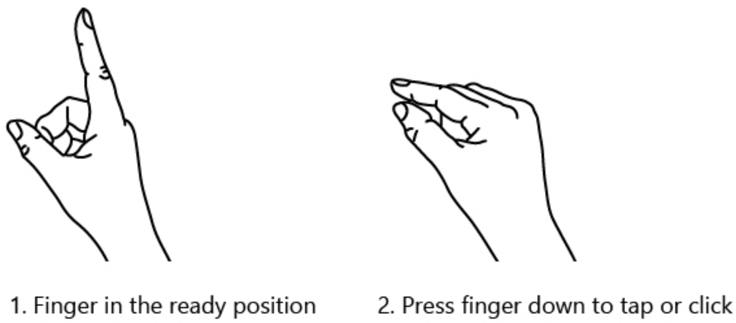


Figure 12. Air Tap Mechanic. Source: [41]

The Bloom gesture is used primarily to go back to the Home screen, bring up the Application menu, or to exit out of a current application. It is the same as pressing the Home button on an Android device, or the Windows key on a Windows machine. This bloom gesture is not often used in applications because unless otherwise coded, the gesture will minimize the application and bring up the Windows 10 mobile screen. As shown in Figure 13, the user holds their hand palm out, presses their fingers together, and once stable, the user will then bring the fingers outward.

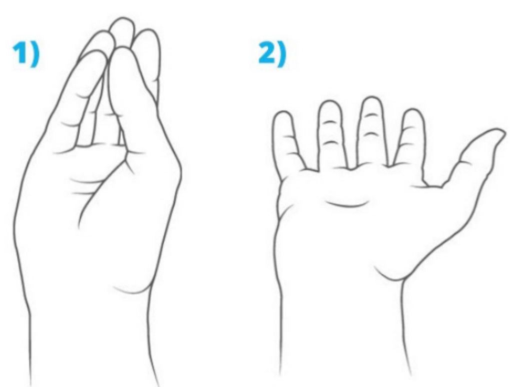


Figure 13. Bloom Gesture. Source: [41]

3. 3D Environment

All objects created for the prototype were initially built in Blender, and then imported into Unity to be ultimately deployed onto the Hololens. Once imported into Unity, the objects were scaled to fit the augmented environment, and then positioned within the camera bounds to ensure maximum visibility for the user. The objects were placed approximately 5ft directly in front of the user's visual plane, and approximately 1ft below the user's eye level. This placement ensured the user could see the OT network displayed on the 1st Deck of the DDG model as well as be able to effectively visualize each deck below.

a. DDG Model

The base DDG model was initially given to us by Naval Sea Systems Command Carderock Division (NSWCCD), and then heavily modified in Blender by the Futuretech team at the MOVES Institute to create decks and compartments suitable for visualizing a realistic DDG OT network. The model consisted of 1,6178,701 polygons, with four decks, over 50 compartments, and an encased hull with a rudder and two screws. Figure 14 is a screenshot taken from Unity showing the entirety of the model. The models shown in the figures of this research are not entirely accurate representations of a current USN DDG, and are not scaled down to match current specifications. However, participants of the usability study were provided with accurately represented models in their scenarios.

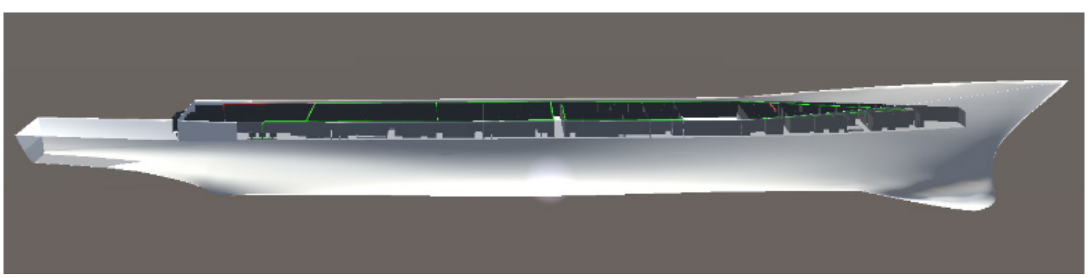


Figure 14. DDG Model used in Prototype

b. Integrated OT Network

Once the DDG was built in Blender, the next step involved developing the framework for the OT network that would become the basis for the scenario in the usability study. This network was also primarily built in Blender, using long cylinders to represent the physical Cat5/Fiber/Coax cableways, and small spheres for physical switches and hubs. The 3D models for ship systems and servers were free to purchase, and were found on Turbosquid [42]. Figure 15 and 16 show the OT network overlaid on the DDG model, with red/green cableways simulating operable and inoperable ship systems.

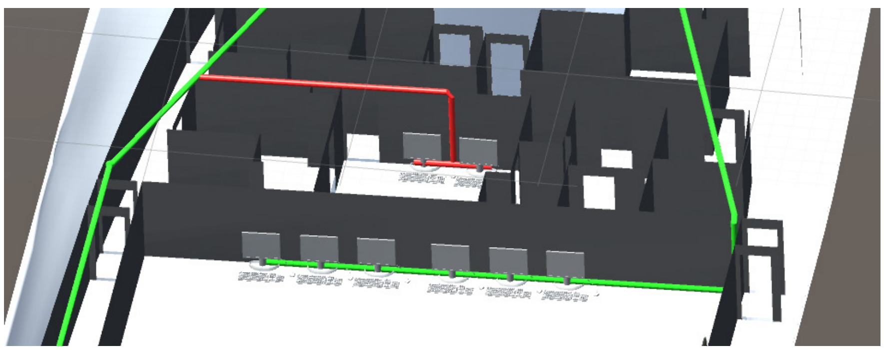


Figure 15. OT Network Ship Systems

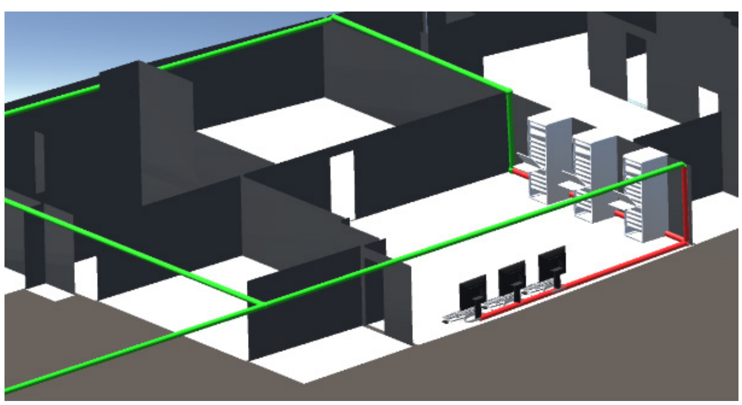


Figure 16. OT Network with Main Servers

c. Rotation Wheel

At the aft of the DDG model is a circular wheel that allows users to request a rotation of the DDG/OT network; discrete rotation points represent rotations of 45° between two neighboring points on the wheel, with a starting point of 0° and the last one representing a rotation of 315°, all pivoting around the horizontal axis of the DDG. The wheel represents a collaborative tool—any rotation is replicated and visualized for all team members, allowing them to decide which angle is best for their task. Figure 17 shows the wheel with green squares representing potential rotation angles (discrete levels of rotation), and the red square representing the current model position (rotation).

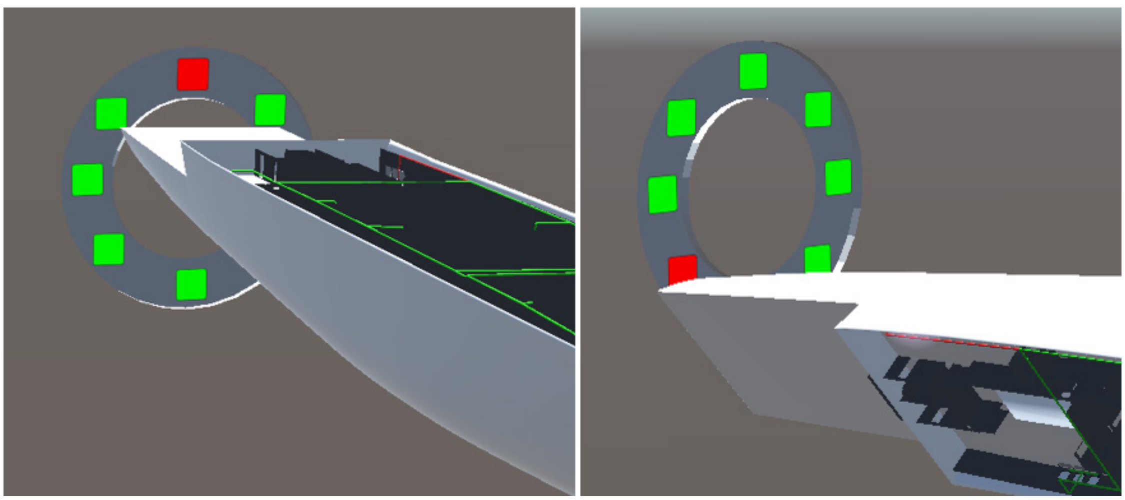


Figure 17. Rotation Wheel: (a) 0° Rotation, and (b) 135° Counter-Clockwise Rotation

4. Heads-up Display (HUD)

Each individual user required a set of options that would give them control of their virtual environment. In early development, the visualization of these options began as static options in the virtual world space, but we decided that as the user moved around the models they should be able to manipulate the models without changing their primary view. This was achieved using a Tagalong/Billboard script attached to a menu with a set of selection buttons, which followed and constantly faced the user as they traversed the scene. It also was important that some of these options were individually viewed and selected (they acted as private views), whereas others were collaborative. In this way, users can always collaboratively view the model, but can also individually query objects and view information about separate decks to develop necessary cyber SA. Figure 18 shows the prototype HUD with a portion of DDG model in the background.

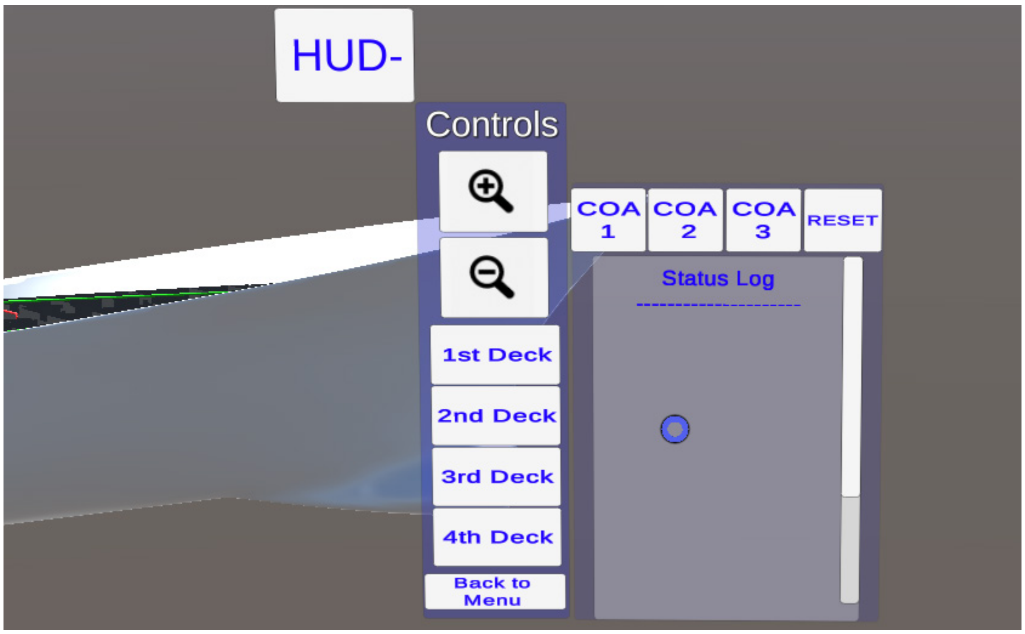


Figure 18. Prototype HUD

5. Controls

The DDG model and associated OT network are visually complex, therefore users needed controls to identify network objects, add and remove decks, and zoom in/out to isolate and accomplish their tasks in a timely manner.

The DDG model used in this prototype had four decks, each with its own ship systems often interconnected with the decks above and below. Due to the specificity of tasks, we made each deck a toggleable view, with only the first deck and the hull appearing at the start of the application. This system of controls gave users the ability to view one deck at a time or examine the ship as a large system with all decks visible. In case a majority of the model was inside field of view, the number of Frames per Second (FPS) displayed (i.e., the frame rate dropped). By allowing the individual to choose only the necessary set of information (3D objects) to be displayed, we also provided a technique to maximize prototype performance.

The zoom options granted the users the ability to zoom collaboratively—if one user zoomed the model in or out, then the DDG model for every user would appear zoomed in or out. As more 3D objects were integrated into the model, the scene became more crowded; this resulted increased the relative difficulty of correctly selecting individual objects. By allowing the users to zoom in on the scene, they were able to accurately select objects and review individual compartments of the DDG in greater detail.

a. Status Log

The ship systems incorporated throughout the model were visually identical. Each system was represented by a set of 1–3 computers with attached keyboards, and no other individually identifiable characteristics. Because of this, it was crucial that the prototype provide a way to quickly identify the system without needlessly distracting the user from the task at hand. Whenever a user gazed at an object and air-tapped or clicked it, the status log provided this service by listing the name of the system. Each time a user selected a system, the name would appear on the bottom of the scrollable log, as seen with the list of systems in Figure 19.

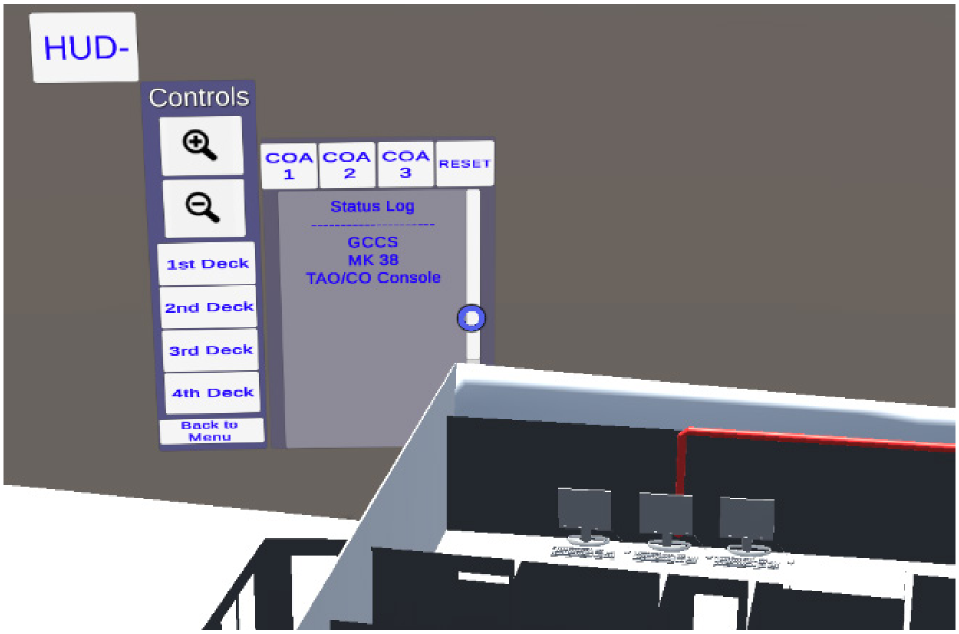


Figure 19. Status Log

In this way, the user could also look back at the history of their selections and keep track of their prior status.

E. SYSTEM TESTING AND PERFORMANCE

1. Hololens Operability

The Hololens is a revolutionary device for the AR development community, with a small form factor and impressive processing power. However, during the development of this prototype, several operability issues were discovered and later remedied to enable collaborative visualization for multiple users.

The basic Hololens hand gestures are simple and effective, but they are not recommended during long tasks or when a user needs to be accurate in object selection. Even using the air tap gesture to select objects or manipulate the models, arm fatigue becomes a real hindrance to effective task completion, and users end up using the clicker instead. Compared to the Hololens, other AR devices such as the Magic Leap and Meta incorporate more robust gestures into their interfaces to support movement of models and interactive physics. The use of the air tap within our prototype was also quite often not recognized, which resulted in most users primarily using the clicker for input control in our application.

The Hololens is equipped with a 802.11ac Wi-Fi card and Bluetooth 4 capability, but native support for collaborative model sharing or Hololens-to-Hololens communication is nonexistent. Microsoft developers were forced to build a toolkit to provide the framework for other users, and even with the toolkit, sharing coordinates or anchors was not simple. We foresee that user collaboration will be a key motivator for developers and industry to use Hololens in the future, so providing a shared experience that is relatively easy to develop would be an enormous boon. For this prototype, we heavily modified the collaborative anchor sharing, model modifying, and object spawning network code found in the Hololens Sharing tutorial [43].

2. Network Testing

When the prototype was first being developed, the Hololenses were connected to the Naval Postgraduate School (NPS) wireless network as show in Figure 20, and everything was working fine, although very slowly.

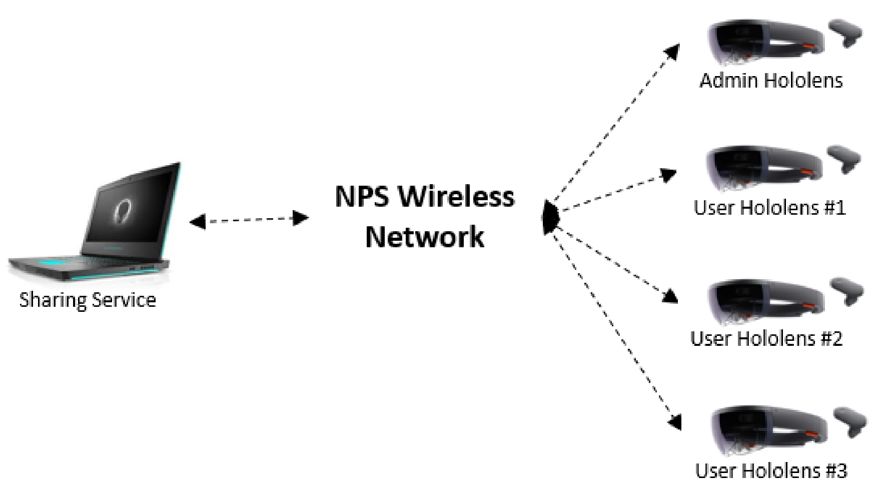


Figure 20. Initial Design of System Architecture

Messages were being broadcast between the Hololenses, but it was taking a few seconds to deliver a message; downloading the anchors was a tedious process as well. This severely impacted the user experience and made the design of the system much more time consuming. In addition, when moving the demonstration between buildings on the NPS campus, the dynamic settings of the NPS wireless routers modified the IP addresses of each Hololens as well as that of the server. Due to the way that we built the server, the IP address was hardcoded into the build, so once the server IP changed, the script had to be edited in Unity and the application had to be rebuilt on each Hololens. These two issues convinced us to abandon that approach, and instead build a small LAN as seen in Figure 21 using a wireless router. This made moving the system to a new location very simple, and the broadcast process very fast.

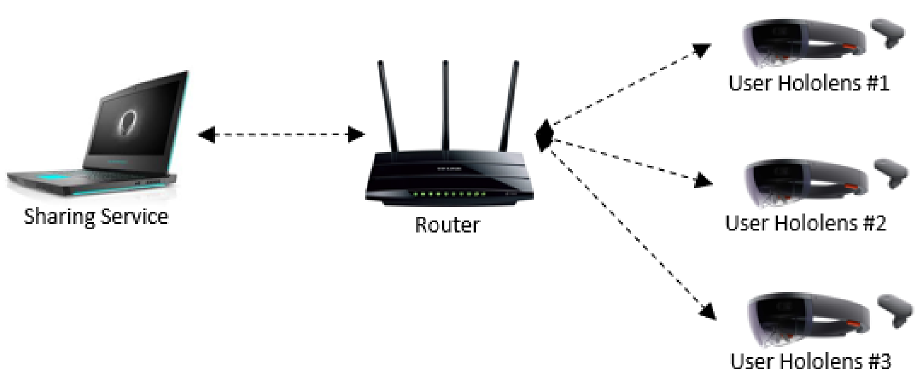


Figure 21. Hololens LAN Concept

Once the network architecture shown in Figure 21 was established, and it allowed packets to be broadcasted to all Hololenses in the Shared Experience, we conducted the tests to ensure that the network's anchor sharing capability could support as few as two, or as many as five Hololenses simultaneously. These tests were an initial success, but we determined that the order in which the Hololenses entered the Shared Experience mattered to the stability of the anchor sharing mechanism. To achieve better control during the Usability Study, we decided to add an Administrative Hololens controlled by a proctor who would initialize all of the scenes, and after each subsequent user entered the scene, they would import the Admin's initial shared anchor.

3. Scene Operability

This prototype is organized into three separate scenes in Unity: Menu/USN Splash Screen, AR Training, and Scenario 1. When a user initially starts the application, the "Made in Unity" screen appears for approximately five seconds, and then the splash screen appears with options to select AR Training or Scenario 1 as shown in Figure 22.

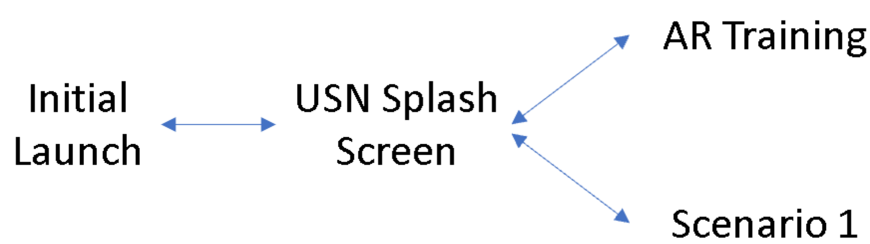


Figure 22. Unity Scene Management

Within the AR Training/Scenario 1 scenes, HUD menu buttons allow the user to exit the current scene and open the splash screen. This allows a user to transition from AR Training to Scenario 1 without completely exiting the application.

After testing scene management with users transitioning between the splash screen and main scenes, we discovered that the server could not consistently manage anchor import requests from multiple, simultaneous users. To remedy this issue, we used the Admin Hololens to build the scene, and requested that users enter the scene one at a time and complete their anchor import before allowing another user in. We also noted during this testing that if a user entered a different scene than the other users (for example one enters AR Training, and the others enter Scenario 1), whichever scene contains the first uploaded anchor will always be the main anchor. To remedy this, we created separate virtual rooms for each scene in Unity. In this way, if two users entered one scene, and two users entered a separate scene, they would import and upload anchors to only those in their virtual room.

4. System Performance

Currently, Hololens system performance is not well documented, especially in the case of multi-user collaboration. Very early during our system development, we incorporated FPS logging into Unity as seen in Figure 23; we collected the data from the initial launch of the Scenario 1 scene, until the termination of the scene, and documented the performance life cycle.

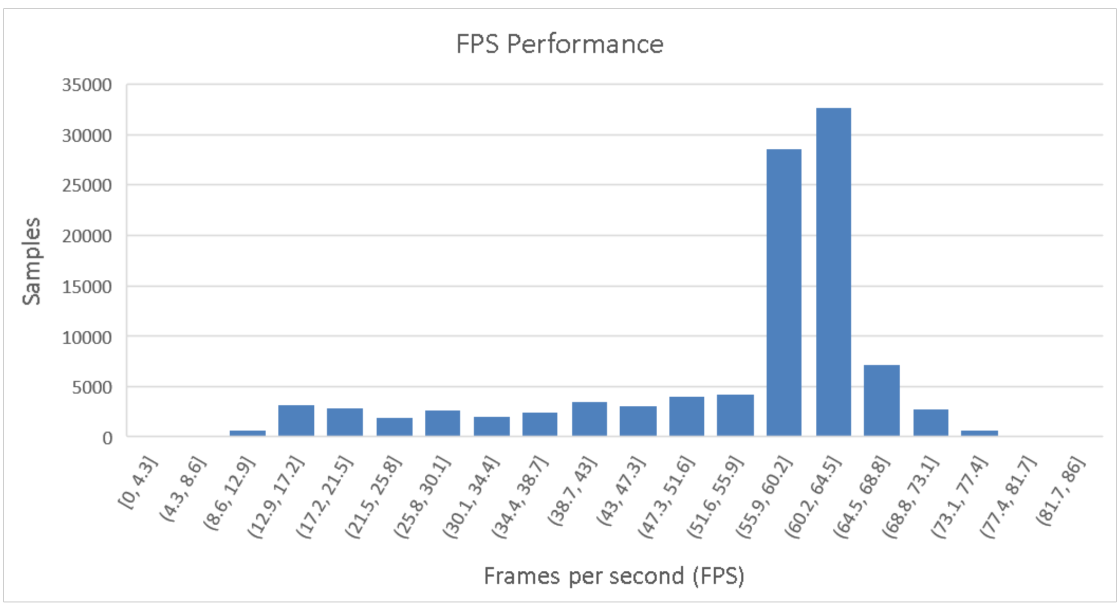


Figure 23. FPS Performance during Prototype Use

The visual FPS spans from 1fps to 76fps as show in Table 1, but during times of relatively small user movement and no model changes, it is approximately 60fps. As the model becomes more complex by adding decks, or at the instance of removing them, the FPS drops to 30–50 for a split second, and then returns to between 55fps and 65fps. As other users enter the environment, the performance of the application does not decrease. We believe this is an important statistic, because it indicates that even with say 50 concurrent users, there would be no additional complexity to the displayed graphics for the individual Hololenses, but the number of messages being sent by all of the users simultaneously would have a high likelihood of disrupting the network performance between the server and clients. This was seen on a smaller scale during testing when two users attempted to request anchors simultaneously. The simplicity of the model, and prototype application may be major factors to these statistics. While testing, CPU and GPU processing speeds were tracked during application run-time through the performance graphs seen in Figure 24, but were not logged during the user study.

Table 1. FPS Statistics

Minimum	1 fps
Maximum	76 fps
Average	53.36 fps

Figure 24. Hololens System Performance on Windows Device Portal (WDP)

V. USABILITY STUDY

A. INTRODUCTION

This chapter presents the design, experiment methodology, and results of the usability study for the Network Visualization prototype described in Chapter IV. A goal of the study was to evaluate usability of the interface developed in support of network visualization in a context of real-world scenarios in Naval domain, in which the prototype could possibly be very valuable collaborative tool. We decided to test the prototype with the domain users—having realistic end users as participants in the study was the most effective way of identifying usability problems and getting the most relevant feedback for the future iterations of this prototype. Our hope was also that the results and insights gained in this study could be applied to a range of tasks that are similar in nature to the task studied in this research effort.

B. INSTITUTIONAL REVIEW BOARD (IRB) DOCUMENTATION

Prior to conducting the usability study, NPS requires that any research which involves human subjects must go through the Institutional Review Board (IRB) review process. This process includes building out the following documentation:

1. IRB Application
2. Scientific Review Form
3. Conflict of Interest Disclosure Form
4. Informed Consent Form
5. Recruitment Flyer (Appendix A)
6. Recruitment Email
7. Simulator Sickness Questionnaire (SSQ) [44] (Appendix E)
8. Demographics Questionnaire (Appendix B)

9. System Usability Scale (SUS) Questionnaire [45] (Appendix C)

10. Post-Task Questionnaire (Appendix D)

After submitting the required documentation, we were approved to begin with the study in October of 2018.

C. PARTICIPANTS

The usability study involved 30 USN personnel, from the ranks of O-1 (ENS, one person) to O-5 (CDR); all individuals recruited for the study had previous shipboard experience. The study was advertised to USN students through the NPS Muster Page, mass emails, personal exchanges, and recruitment flyers (Appendix A). All sessions occurred between 2–23 October of 2018 at the MOVES Institute at NPS, Monterey, CA. All 30 participants who started the study were able to complete it successfully.

The ages of the participants ranged from 22–44 years old, with the average age of 32.4 years old (Figure 25 and Table 2). This is a normal range for USN Officers and demonstrates that we did not have any participants either too young or old to participate in the study.

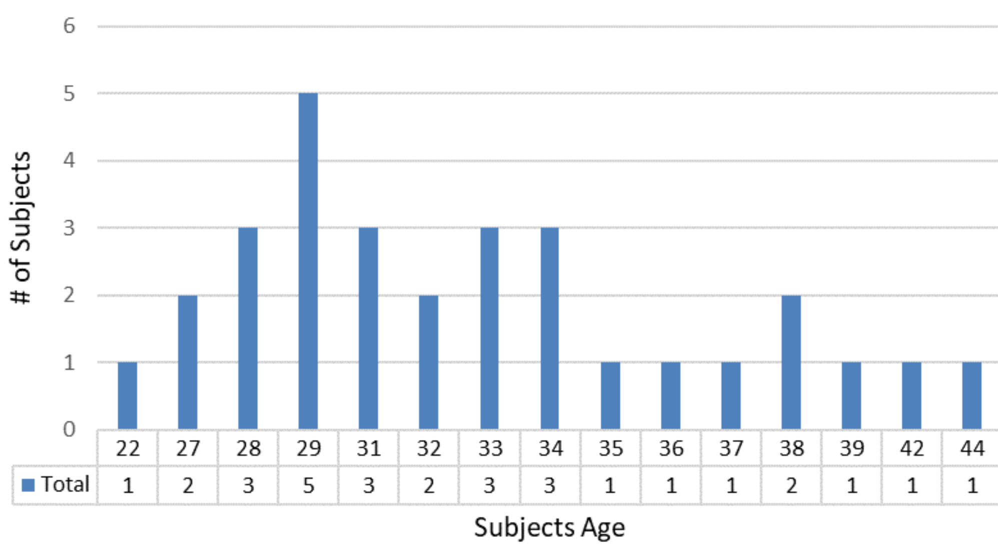


Figure 25. Subjects' Age Statistics

Table 2. Subjects' Age Statistics

Minimum	22 yrs
Maximum	44 yrs
Average	32.4 yrs
Average	9.8 yrs

Participants' years of service ranged from less than a year, to 23 years, with an average of 9.8 years (Figure 26 and Table 3). All of the participants have spent some amount time on a USN vessel, with most of them having multiple tours of service on different types of vessels.

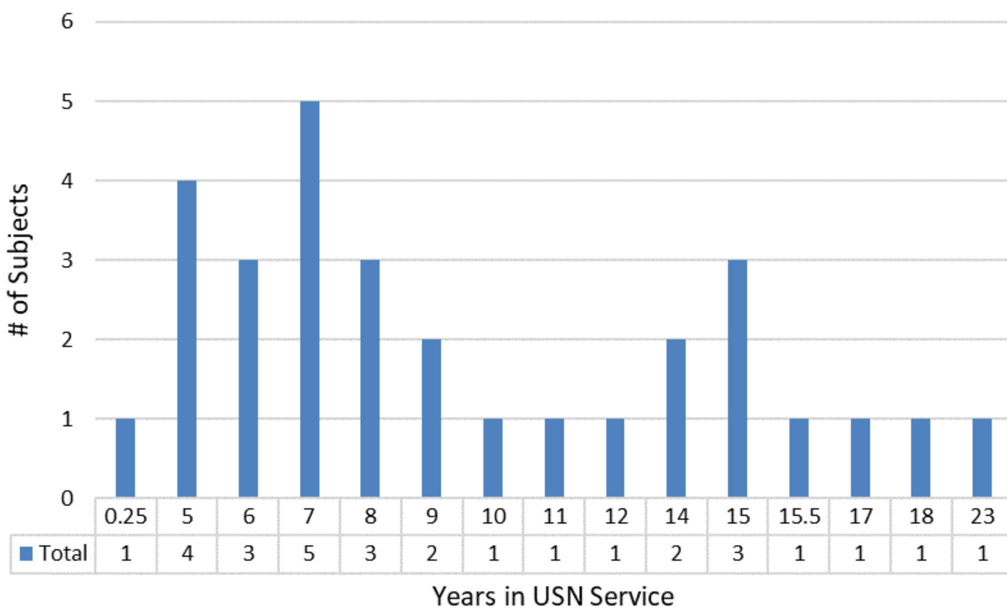


Figure 26. Subjects' Years in Service

Table 3. Subjects' Years in Service Statistics

Minimum	.25 yrs
Maximum	23 yrs

The participant's USN ranks ranged from Ensign (O-1/ENS) (0-2 years of service) to Commander (O-5/CDR) (15+ years of service), with a vast majority holding the rank of Lieutenant (O-3, LT) (4+ years of service) as presented in Figure 27. This demonstrates that all individuals had the knowledge required for the DDG network task that was central for the study.

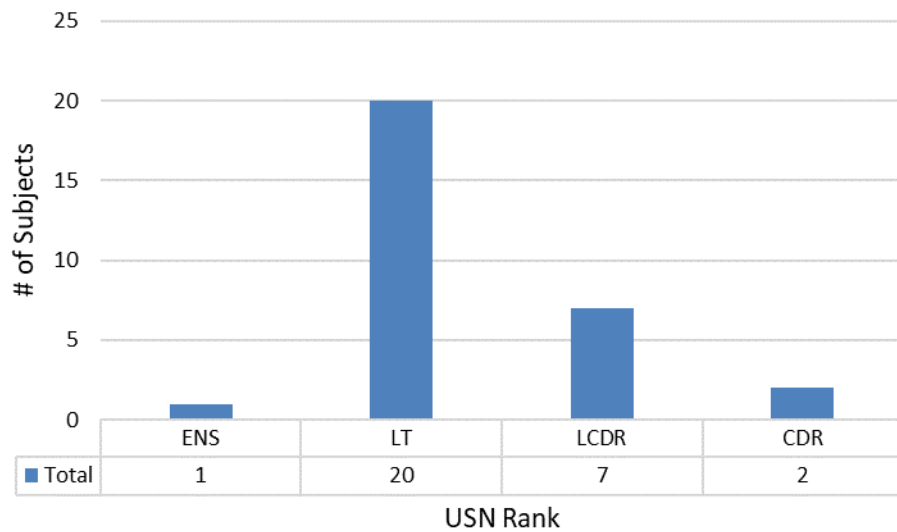


Figure 27. Subjects' Rank Statistics

Each study began and ended with participants in groups of three, with individual participants in each group having equal collaborative roles (i.e., there was no assigned superior or supervisor).

D. STUDY DESIGN

1. Virtual Environment

The virtual environment for this study was designed to ensure that participants were focused on specific objects and their tasks, and not be distracted by the details and geometry that were not essential for the task performance. There were three scenes in our environment; the first was a splash screen which allowed the participants to navigate to the other two scenes, the second was a training environment that allowed the participants to learn how to navigate through the space while viewing 3D geometry, execute the type of object manipulations that was to be used in the main task, and the third was the main environment that supported collaborative network task. The details of the scenes and their models are provided in Chapter IV.

2. Tasks

During the study, the participants performed two tasks: a very simple collaborative task performed during the training session, and a more complex collaborative network task undertaken during the main experimental session. The participants were given precise instructions for how to accomplish each task; there were no time limits for either task.

For the training session, the participants were asked to collaborate on a task that involved changing the colors of a series of cubes on the left as seen in Figure 28; those colors had to match a combination of colors shown on a set of cubes to the right.

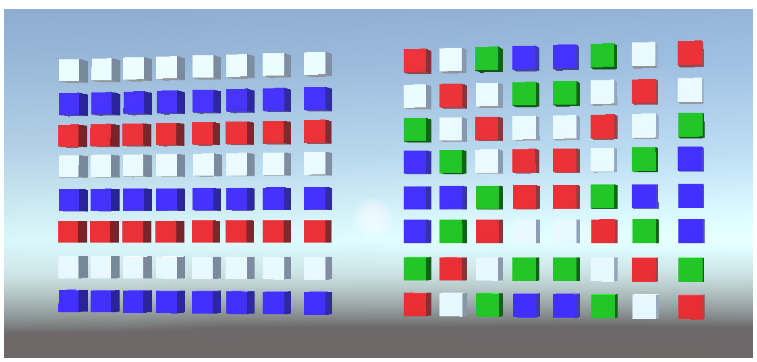


Figure 28. Training Session Task: Colors of the Cubes on the Left Had to Match the Colors of the Cubes on the Right

This session involved training the participants in how to gaze at each cube, allow the cursor—an indicator of gaze vector—to be positioned over any cube, and then either use the clicker or the air-tap hand gesture to signal the system that the cube was selected. Each click would cause a change of the color from the ‘current’ color to the ‘next’, one color change per click (white color would change to red, red to blue, blue to green, and green to white). This was not a complex task, and all ten groups were able to accomplish it quickly without any errors. The collaborative environment gave the participants the freedom to choose which cubes they wanted to change, and allowed them to discuss the strategies for how to split the workload among themselves. The work could have been completed by a single individual; however, the number of cubes implied that it would be finished more quickly if the entire team collaborated on it.

The main task was more complex, and assumed that all individuals had prior knowledge about the computer networks on a USN DDG. The participants were required to collaboratively work together using the DDG model and associated OT model. At the start of the scenario, there was a non-operational network component that was required during the scenario to be fully operational. To bring this component to a fully-operational status, other portions of the OT network were brought down. The participants were to discuss and recommend a Course of Action (COA) to the CO of the DDG (the CO was represented by the proctor of the study). Three possible network COAs were available and the group had to select the most appropriate network COA for a given situation. Each COA caused certain elements of the network to become non-operational, and others to become inoperable. Two operational situations were given to the participants (one at a time), and three COA's available to choose from were identical in both situations. A whiteboard was provided so that participants could write out their thoughts and increase visualization of the differences between COA's, as well as note the operational status of each system in the OT network.

As the scenario was initialized, the participants were put through an introductory process during which the proctor explained the aspects of the scene that were different than the training session. Once the participants were given the freedom to begin their task, they transitioned into a series of actions (not necessarily in this order):

- Customize the model view to benefit all team members.
- Discuss the operational requirements of each scenario.
- Identify the current state of the OT network, including the systems that are up or down.

- Load each COA in succession and identify what elements of the network the COA brings up operationally, and what brings it down.

- Discuss each COA in succession against an advantages-disadvantages list and choose the best solution for the operational situation at hand.

- Explain to the CO which COA was best in this situation, and why.

After briefing their best COA to the CO, their task for the scenario was complete. The experimental session had two scenarios, and completion of both scenarios marked the end of the experimental session.

3. Apparatus

The usability study involved three participants and the proctor, each wearing a Hololens. Those of the participants were identifiable by markings, as shown in Figure 29. We conducted preliminary tests prior to the usability study and determined that red, green and blue markings on Hololenses did not allow for easy identification, so they were not used. Instead we opted for having one Hololens-clicker pair with a solid blue tape identifying it, one had white tape with blue stripes, and the last one had solid white tape. In all cases, tape was applied to both sides of the Hololens and easily visible in videos that were recorded. The proctor's Hololens was not marked in any way to avoid misidentification in post-task video analysis.

Figure 29. Hololenses Employed in Usability Study

Participants moved in a rectangular workspace that was approximately 14.5ft x 11ft large, bordered by a standup desk that housed the server and router (Figures 30 and 31.)

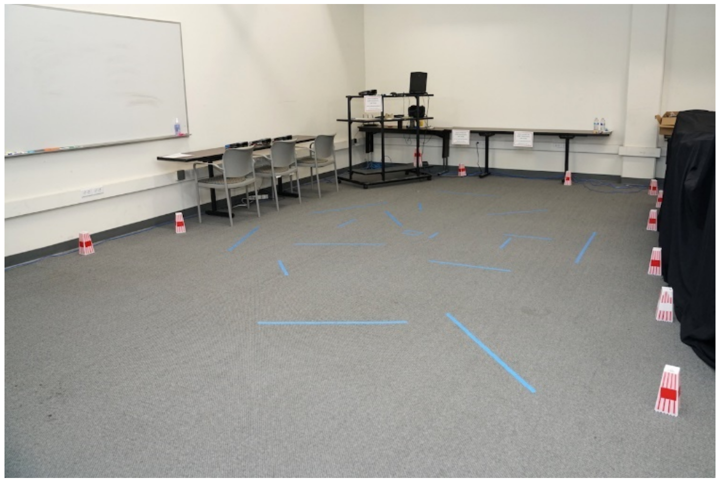


Figure 30. Usability Study Workspace (front-facing)

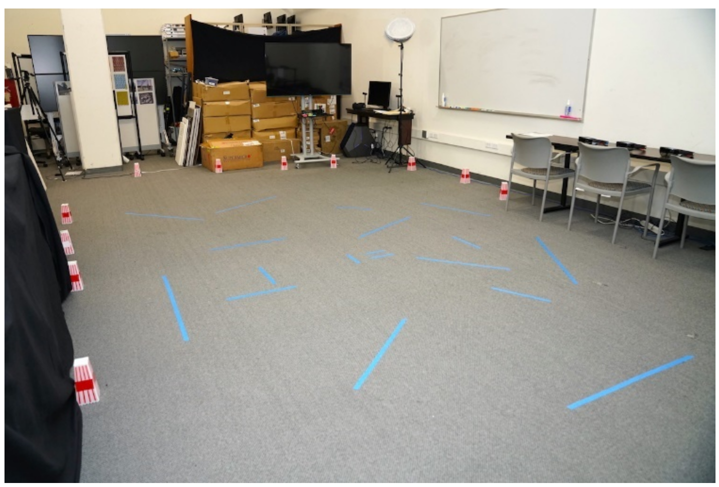


Figure 31. Usability Study Workspace (back-facing)

The floor of the workspace was marked with randomly distributed blue tape pattern to provide the Hololens with more distinct visual information in which to accurately place and share the model anchors, as well as to provide a convenient spatial reference for the recorded sessions. The desk on the right of Figure 32 was used to house the Hololenses when they were not in use; it was also used by participants when they filled out the questionnaires. The whiteboard shown in Figure 31 was presented to the participants as an optional tool available for completing the tasks.

Figure 32. Participants in Usability Study: The Experimenter (proctor) and Three Team Members

4. Objective Data Set

The objective data included detailed system logs of each participant's UI interaction during the study. As soon as the participant entered the main scene in any scenario, the collection of system logs began, and the logging of interaction events ended when the scene was exited. These system logs were saved to the internal Hololens memory, and they were later extracted for data analysis.

The system logged the following objective data sets:

1. Time stamp when scenario began

2. Time stamp when scenario ended

3. Hololens display FPS every ~0.05s

4. Time-stamped event of each menu button selection (selection of menu items was done either by using the clicker or by hand gesture)

5. Time-stamped event of each control button selection (selection of control buttons was done either by using the clicker or by hand gesture)

5. Subjective Data Set

Subjective data was exclusively collected via the questionnaires approved through the IRB. Once the questionnaires were filled out, the proctor transcribed them into quantifiable data sets in an Excel spreadsheet for easy manipulation and analysis. A set of questionnaires used in the study included:

1. Baseline and post session Simulator Sickness Questionnaire (SSQ) [44]

2. System Usability Scale (SUS) Questionnaire [45]

3. Demographics Questionnaire

4. Post-Task Questionnaire

E. PROCEDURE

1. Pre-experiment

The steps executed by each participant during the usability study consisted of the following:

1. Each participant was given a packet of questionnaires as they arrived at the usability study location. They were instructed to complete the Consent Form first, and then to await further instructions. If all three participants accepted the conditions, we proceeded with the study (5 min).

2. Completion of the baseline SSQ (2 min).

3. Initial Hololens training. This included how to wear the device, power it on, and perform basic recognizable hand gestures (5 min).

4. Familiarization with the Hololens interface, HUD, and gaze selection mechanisms. Participants experienced initial splash screen seen in Unity in Figure 33 and during the study in Figure 34. Thanks to the optical see-through display, the real world could be seen in full detail.

Figure 33. Splash Screen Scene in Unity

Figure 34. Splash Screen as Seen Inside Hololens

5. Participants complete the cube color training session as seen in Figure 35 (5mins).

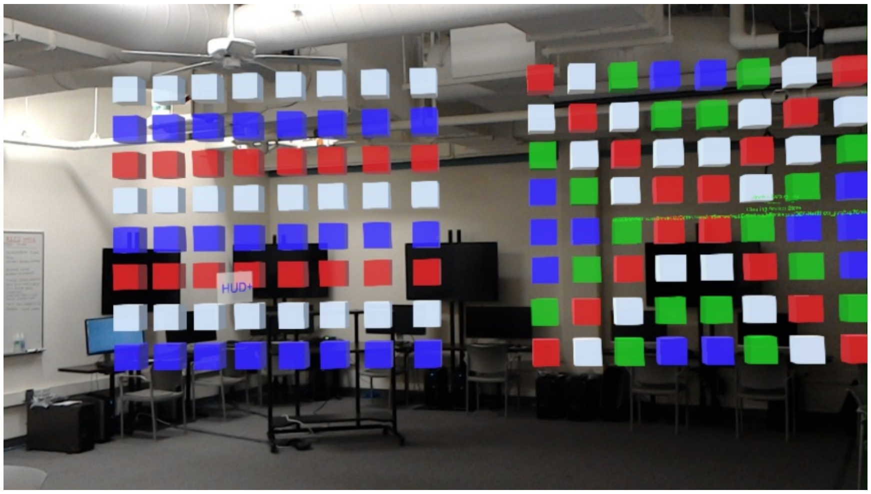


Figure 35. Training Session Environment as Seen Inside the Hololens

6. Main experiment instructions are given to all participants.

7. Execution of the network scenario in the AR environment as seen in Figure 36 and 37. Icon HUD+ could be selected and expanded to provide detailed HUD information and its control menu.

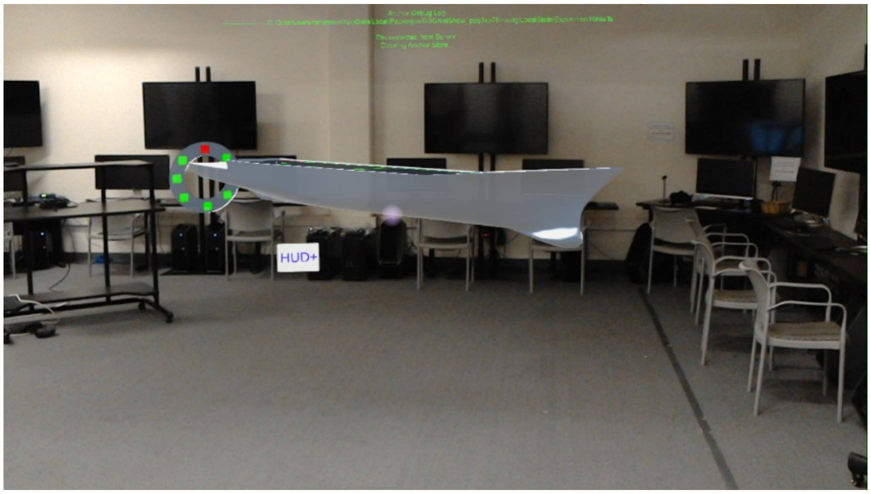


Figure 36. Main Environment as Seen Inside Hololens, Side View

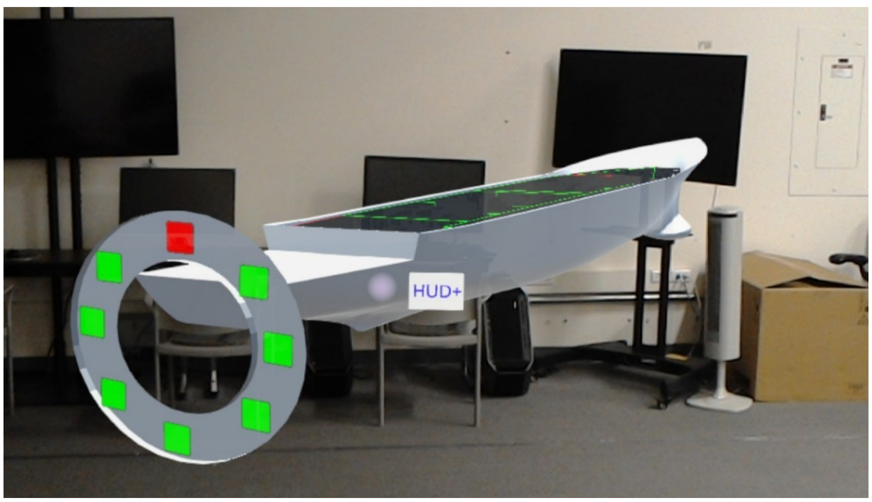


Figure 37. Main Environment as Seen Inside Hololens, Front View

8. Completion of the post-task SSQ.

9. Completion of the Post-task Questionnaires: the SUS Questionnaire and the Demographic Questionnaire.

10. Participants given a short debrief/explanation of the study and were allowed to ask questions.

F. RESULTS

1. Objective Data Set

The data in Figure 38 was taken from one participant during the main scenario of our usability study; Figure 39 represents the first half of the same data set, and illustrates the usual FPS fluctuations that were encountered by participants during the study.

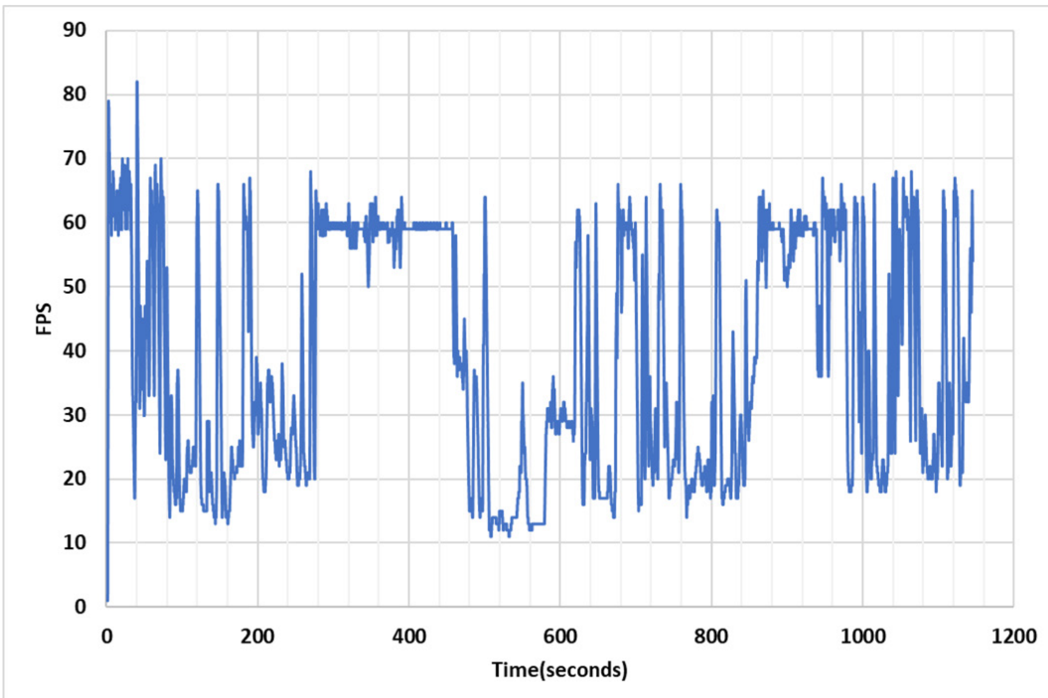


Figure 38. Frame Rate Graph during the Main Scenario for One Participant

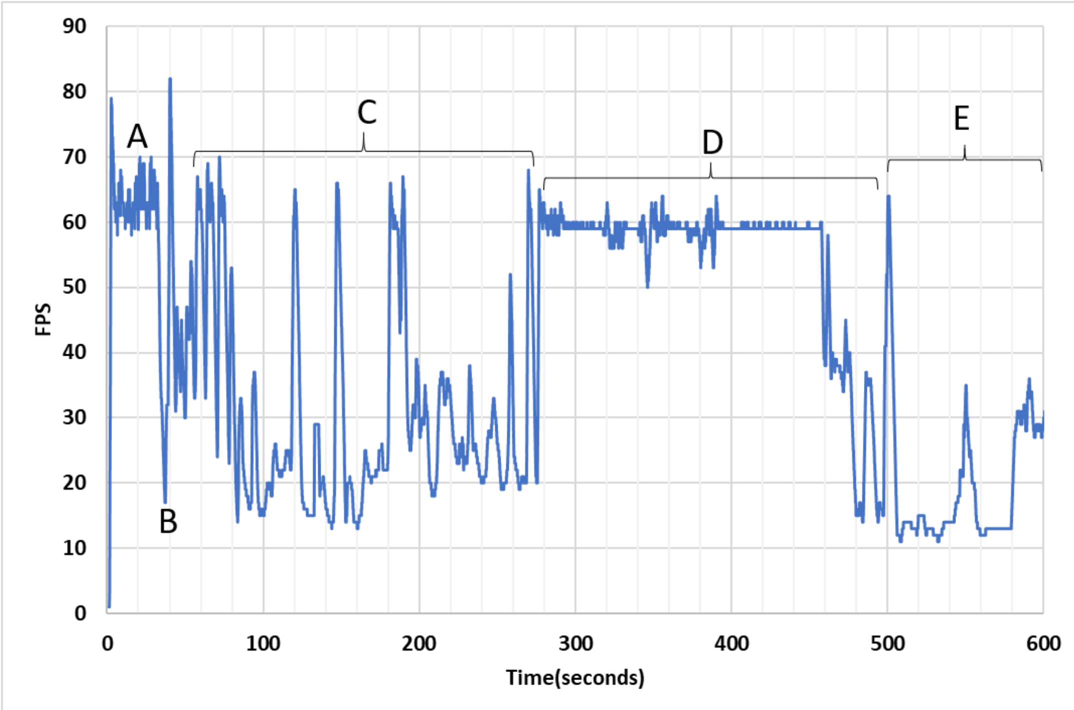


Figure 39. Fluctuations in Frame Rate during First 10 Minutes of Main Scenario

At the start of the scenario, the frame rate steadies at around 65 FPS (point A) when the participant is ~5ft from the DDG model, and virtual environment included the geometry of only one deck. As the participant walks closer to the model (point B), the frame rate drops drastically. The participant then steadies the gaze, and the frame rate also steadies to around 45–60 FPS. Point C is an example of the FPS observed as a participant walks around the model, clicking control buttons on their HUD, and removing or adding the decks to explore the elements of that environment. At point D, the participant is not manipulating the model, and also is not moving around the environment, which explains the steady frame rate at ~ 60 FPS. During the time shown at point E, the participant is adding decks to the model while also moving closer. During this phase, the Hololens registers a frame rate drop to just over 10 FPS, and then the frame rate varies anywhere from 10 to 65 FPS. It is readily seen that there is a quite a bit of inconsistency in FPS throughout the scenario, and that it heavily depends on the type of action taken by the participant. Although standing motionless helps preserve the consistency of the frame rate, the biggest attribute to frame rate dropping is the addition or removal of objects into the participant's augmented environment.

Time on task and total clicks by participants during the main scenario was also gathered from the Hololens logs. A click was defined by a participant selecting a button on their HUD, the rotation wheel, or querying the ship systems. Table 4 presents this data, expressing the extreme variance in both data sets.

Table 4. Participants' Clicks and Time on Task

	Total Clicks	**Time on Task**
Minimum	15 clicks	11.1 min
Maximum	193 clicks	46.67 min
Average	78.87 clicks	25.99 min
Standard Deviation	41.07 clicks	9.71 min

The total number of clicks depended entirely on the motivation of the participant during the scenario, as well as their interpretation of the usability of the UI. As shown in Table 4, one participant only clicked 15 times during their approximately 26-minute scenario, while another participant clicked 193 times. Also, due to the differing interactions between participants while completing their task, time on task was widely distributed as well.

2. Subjective Data Set

The following set of questionnaires with self-reported measures, was used:

a. Simulator Sickness Questionnaire (SSQ)

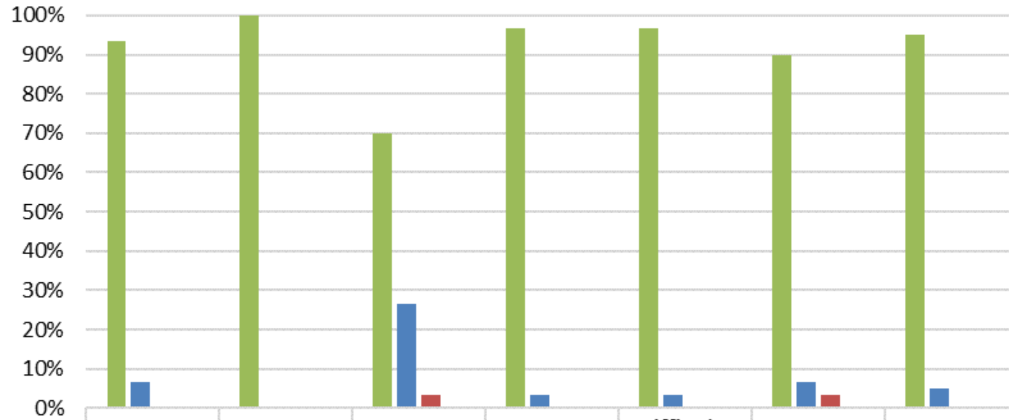
The SSQ given to the participants before and after the study were transcribed and scored according to Kennedy et al.'s scoring criteria [46]. The SSQ consisted of 17 questions which inquired about the severity of different symptoms, which were then categorized to three subscales: Nausea, Oculomotor, and Disorientation. Per Kennedy et al. [46], scores on the nausea subscale are based on symptoms that relate to gastrointestinal distress such as nausea, stomach awareness, salivation, and burping; scores on the oculomotor subscale relate to eyestrain, difficulty in focusing, blurred vision, and headache; and scores on the disorientation subscale are related to vestibular disturbances such as dizziness and vertigo. An average of these subscales produces the total score as presented in Table 5, which is reflects the severity of the symptoms for all participants.

Table 5. Mean of SSQ Scores during Usability Study

Sub-scale	**Score**
Nausea	9.54
Occulomotor	19.96
Disorientation	12.53
Total	14.01

As suggested by Kennedy et al.'s scoring criteria [46], a Total Score of 0 denotes that there are no symptoms present, <5 denotes negligible symptoms, 5–10 denotes minimal symptoms, 10–15 denotes significant symptoms, 15–20 denotes that symptoms are a concern, and >20 denotes that there is a major problem with the simulation. Our data resulted with an average of 14.01 among all participants, which suggested that there was significance to the symptoms described by the participants during the usability study.

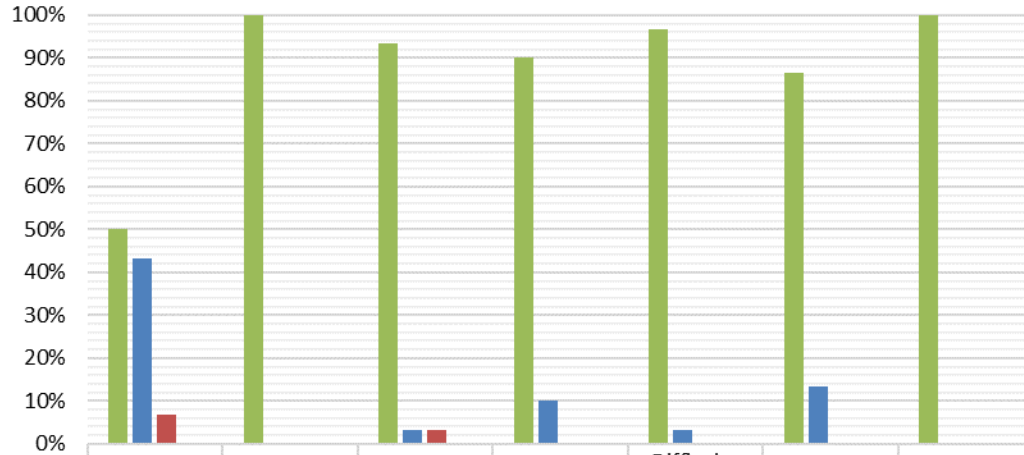
The subsequent charts illustrate the pre- and post-study SSQ results. Figure 40 and Figure 41 communicate SSQ data from the Nausea sub-scale.



	General Discomfort	Salivation Increasing	Sweating	Nausea	Difficulty concentrating	Stomach awareness	Burping
None	93%	100%	70%	97%	97%	90%	95%
Slight	7%	0%	27%	3%	3%	7%	5%
Moderate	0%	0%	3%	0%	0%	3%	0%
Severe	0%	0%	0%	0%	0%	0%	0%

Figure 40. SSQ – Baseline Nausea (before Usability Study)

Interestingly, 30% of participants began the study with slight/moderate sweating, while only 6% ended the study still showing these symptoms. All other participants reported symptoms were ≤10% as shown in the Pre-Study statistics.

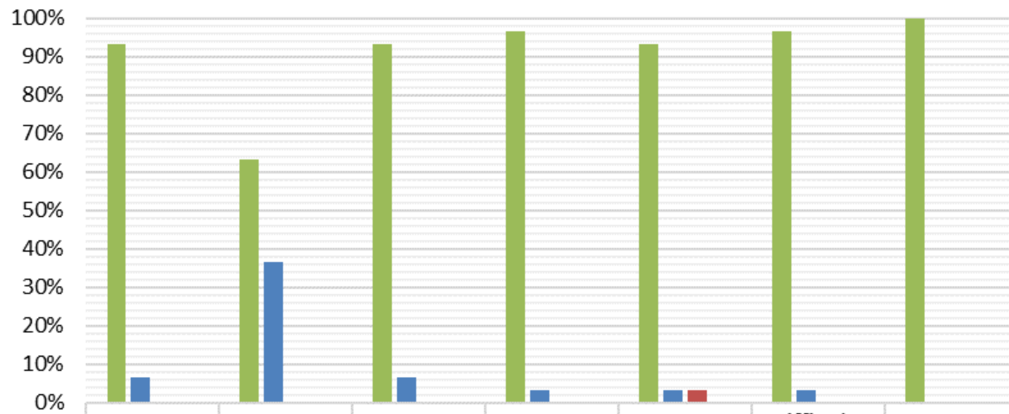


	General Discomfort	Salivation Increasing	Sweating	Nausea	Difficulty concentrating	Stomach awareness	Burping
None	50%	100%	93%	90%	97%	87%	100%
Slight	43%	0%	3%	10%	3%	13%	0%
Moderate	7%	0%	3%	0%	0%	0%	0%
Severe	0%	0%	0%	0%	0%	0%	0%

Figure 41. SSQ – Nausea Post-usability Study

The largest symptom present in the nausea sub-scale (50%) is general discomfort. During post-task interviews, participants explained that the Hololens itself put pressure on their forehead and nose (especially for those with glasses) that made it very uncomfortable after ~15 minutes of use. The SSQ nausea sub-score was 9.54, and the symptoms were considered minimal.

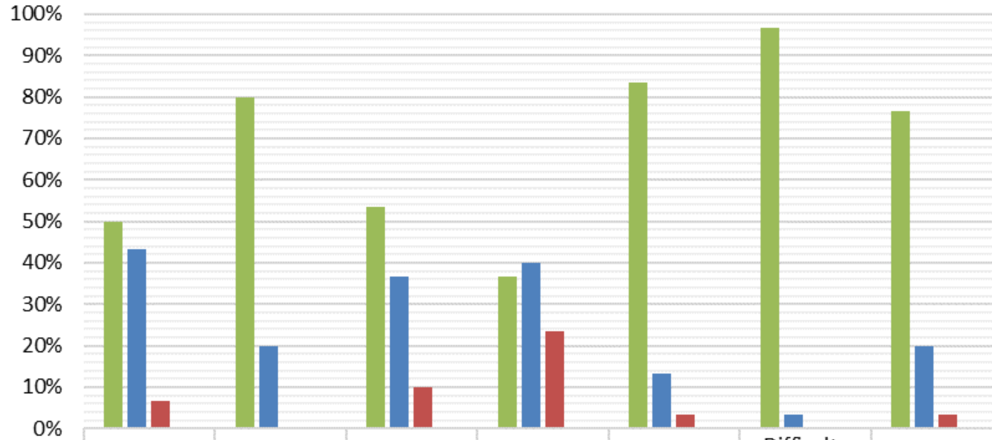
Figure 42 and 43 report the Occulomotor-associated symptoms pre- and post-usability study.



	General Discomfort	Fatigue	Headache	Eye Strain	Difficulty focusing	Difficulty concentrating	Blurred vision
None	93%	63%	93%	97%	93%	97%	100%
Slight	7%	37%	7%	3%	3%	3%	0%
Moderate	0%	0%	0%	0%	3%	0%	0%
Severe	0%	0%	0%	0%	0%	0%	0%

Figure 42. SSQ – Baseline Oculomotor (before Usability Study)

In the oculomotor sub-scale, fatigue presented itself prominently among 37% of participants prior to the study, and although to a lesser extent was revealed as a symptom of 20% of post-study participants. headache and general discomfort were other symptoms seen in 7% of pre-study participants.



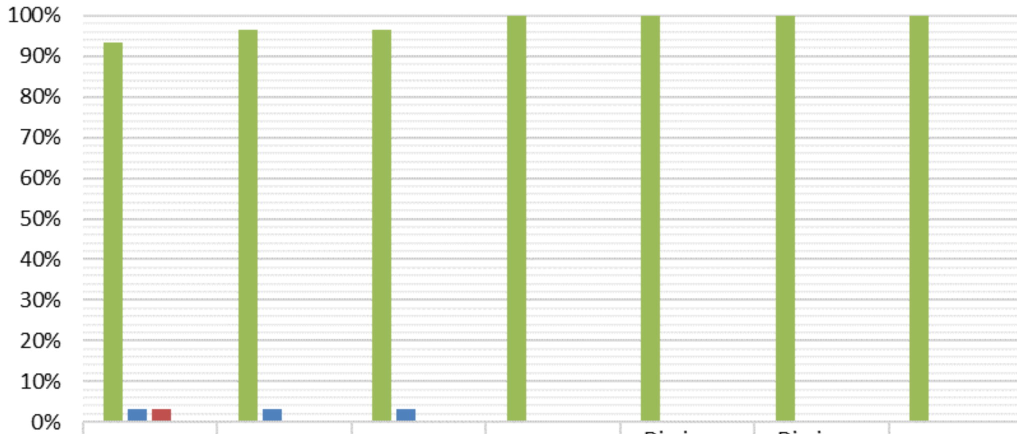
	General Discomfort	Fatigue	Headache	Eye Strain	Difficulty focusing	Difficulty concentrati ng	Blurred vision
None	50%	80%	53%	37%	83%	97%	77%
Slight	43%	20%	37%	40%	13%	3%	20%
Moderate	7%	0%	10%	23%	3%	0%	3%
Severe	0%	0%	0%	0%	0%	0%	0%

Figure 43. SSQ – Oculomotor Post-usability Study

The post-study oculomotor results made the greatest contribution to our high total SSQ score. Over 50% of participants exhibited eye strain symptoms, and headache, and general discomfort was also right around at 50%. These symptoms are significant and suggest that the issues like differences between visual information coming from the real world and simulated world, field of view, as well as the lag and frequently low FPS may have a real impact on participants. Although not tested in our experiment, these symptoms could have had a negative impact on the task as well. The summary SSQ occulomotor score was 19.96, and the symptoms were considered concerning as seen in Kennedy et al.'s scoring criteria [46].

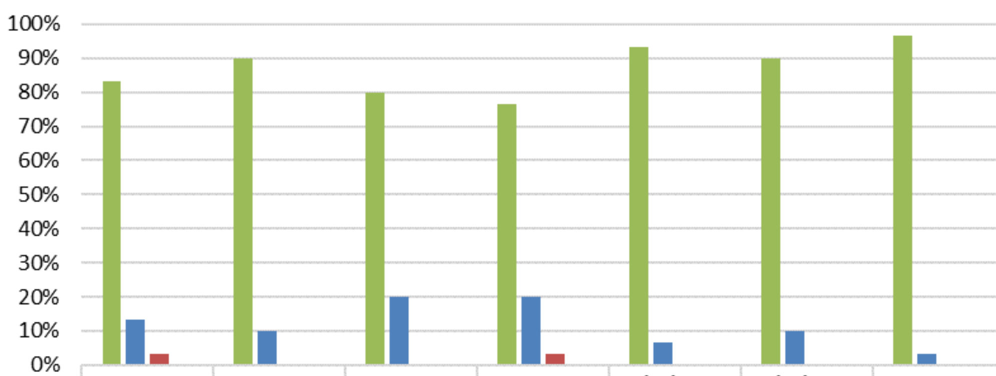
Figure 44 and 45 describe the disorientation subscale of the SSQ pre- and post-usability study.

There were very few reported symptoms in the disorientation sub-scale prior to participants starting the study.



	Difficulty focusing	Nausea	Fullness of head	Blurred vision	Dizziness with eyes open	Dizziness with eyes closed	Vertigo
None	93%	97%	97%	100%	100%	100%	100%
Slight	3%	3%	3%	0%	0%	0%	0%
Moderate	3%	0%	0%	0%	0%	0%	0%
Severe	0%	0%	0%	0%	0%	0%	0%

Figure 44. SSQ – Baseline Disorientation (before Usability Study)



	Difficulty focusing	Nausea	Fullness of head	Blurred vision	Dizziness with eyes open	Dizziness with eyes closed	Vertigo
None	83%	90%	80%	77%	93%	90%	97%
Slight	13%	10%	20%	20%	7%	10%	3%
Moderate	3%	0%	0%	3%	0%	0%	0%
Severe	0%	0%	0%	0%	0%	0%	0%

Figure 45. SSQ – Disorientation Post-usability Study

After the study, 20% of participants experienced fullness of the head and blurred vision. Difficulty focusing, dizziness, and nausea were also present as symptoms for multiple participants. The SSQ disorientation score was 12.53, and the symptoms were considered serious as seen in Kennedy et al.'s scoring criteria [46]

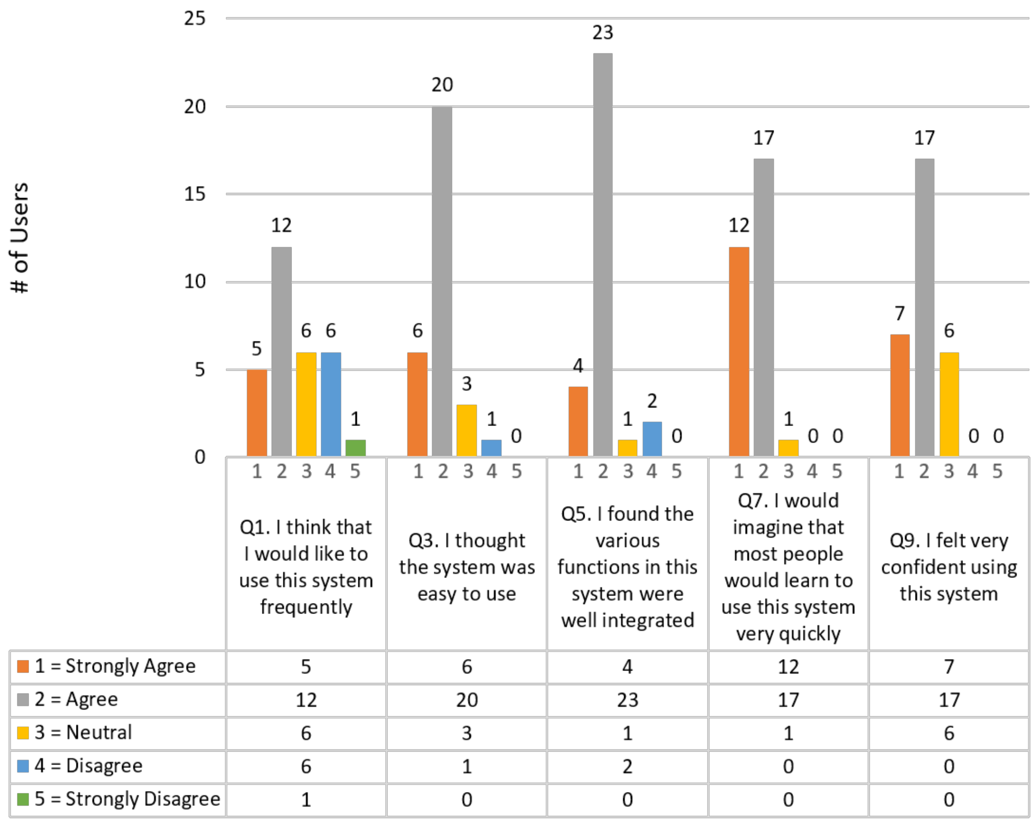
b. System Usability Scale (SUS)

The SUS considers "the context in which a tool is to be used, and its' appropriateness to that context" or "its fitness for purpose" [45]. In the context of the network task described in Chapter III, we wanted to gauge the potential of our tool in resolving challenges in the current operation of the task. We asked a total of 10 quantifiable questions, which we then analyzed to identify areas of success, as well as possible improvements for future iterations of this tool for task-oriented operation. After completion of data collection, the SUS produces a "number representing a measure of the overall usability of the system being studied" [45]. For our prototype, the mean score was calculated to be 74.75 as presented in Table 6.

Table 6. SUS Score for Prototype System

Min	52.50
Max	95.00
Avg	74.75

Figure 46 charts the odd questions from the SUS, and Figure 48 considers the even questions. They both read from left to right with Strongly Agree on the far left of the scale and graphs, and Strongly Disagree on the far right. Table 7 and 8 provide the statistics from the questionnaire, for the odd and even questions, respectively.



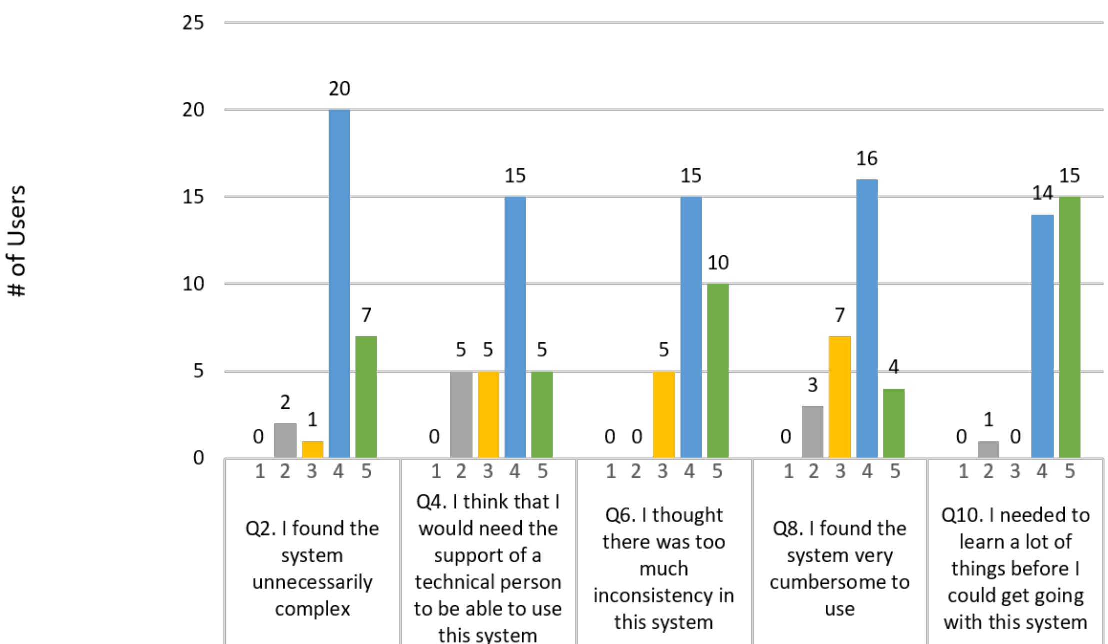
	Q1. I think that I would like to use this system frequently	Q3. I thought the system was easy to use	Q5. I found the various functions in this system were well integrated	Q7. I would imagine that most people would learn to use this system very quickly	Q9. I felt very confident using this system
1 = Strongly Agree	5	6	4	12	7
2 = Agree	12	20	23	17	17
3 = Neutral	6	3	1	1	6
4 = Disagree	6	1	2	0	0
5 = Strongly Disagree	1	0	0	0	0

Figure 46. SUS Results, Part 1

Table 7. Basic SUS Statistics, Part 1

	Q1. I think that I would like to use this system frequently	Q3. I thought the system was easy to use	Q5. I found the various functions in this system were well integrated	Q7. I would imagine that most people would learn to use this system very quickly	Q9. I felt very confident using this system
Minimum	1	1	1	1	1
Maximum	5	4	4	3	3
Average	2.53	1.97	2.03	1.63	1.97
Standard Deviation	1.11	0.67	0.67	0.56	0.67

The data collected in questions 3,5,7, and 9 suggest that all participants overwhelmingly agreed they felt confident using the prototype system, and it was easy to use, well integrated, and simple to learn on. On question 1, a majority of participants agreed that they would like to use the system frequently in network tasks (17), but some dissented and said they would not like to use it frequently (7). Looking at the data from the SSQ, the participant who disagreed with Question 1 had higher than average SSQ scores. We can only speculate that the participants' discomfort during the usability test may have been a factor in the answer to Question 1.



	Q2. I found the system unnecessarily complex	Q4. I think that I would need the support of a technical person to be able to use this system	Q6. I thought there was too much inconsistency in this system	Q8. I found the system very cumbersome to use	Q10. I needed to learn a lot of things before I could get going with this system
1 = Strongly Agree	0	0	0	0	0
2 = Agree	2	5	0	3	1
3 = Neutral	1	5	5	7	0
4 = Disagree	20	15	15	16	14
5 = Strongly Disagree	7	5	10	4	15

Figure 47. SUS Results, Part 2

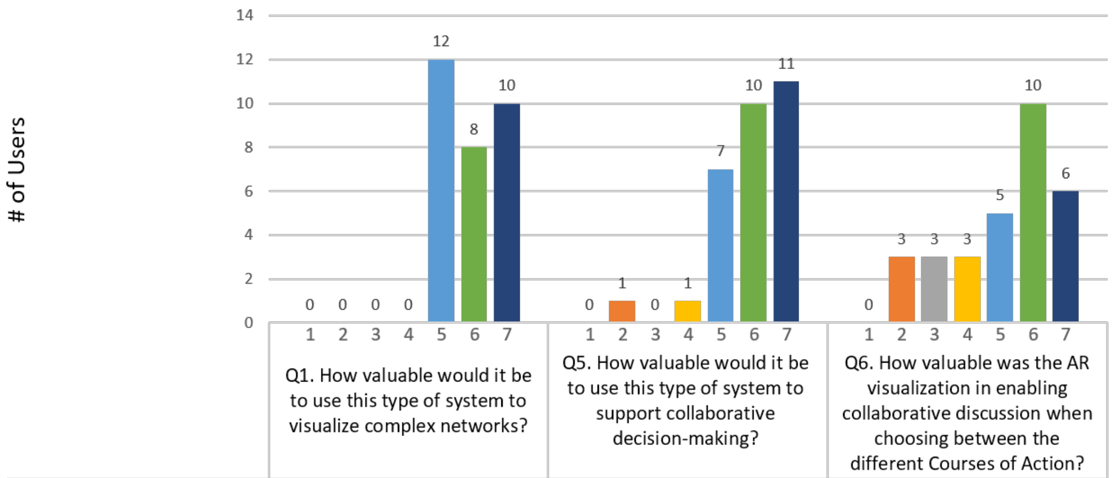
Table 8. Basic SUS Statistics, Part 2

	Q2. I found the system unnecessarily complex	Q4. I think that I would need the support of a technical person to be able to use this system	Q6. I thought there was too much inconsistency in this system	Q8. I found the system very cumbersome to use	Q10. I needed to learn a lot of things before I could get going with this system
Minimum	2	2	3	2	2
Maximum	5	5	5	5	5
Average	4.07	3.67	4.17	3.70	4.43
Standard Deviation	0.74	0.96	0.70	0.84	0.68

The majority of participants expressed their disagreement with statements presented in questions 2, 4, 6, 8, and 10. The participants did not think the prototype system was too inconsistent/complex, or that they would need technical support to use the system. They agreed that the prototype system was not cumbersome, and they would not need to learn a lot of material prior to being able to use it.

c. *Post-task Questionnaire*

The post-task questionnaire was created to determine value, performance, and the ease of use of the prototype system. Each quantitative question was on a 7-point scale, with positive answers lower on the scale then the negative answers. The qualitative questions provided participants opportunity to give descriptive answers. The quantitative data is represented by charts and graphs, and the qualitative data is summarized in a chart. Figure 48 and Table 9 question the perceived value that the prototype had in collaboratively visualizing complex networks to determine a COA and to brief CO in an operational environment. Figure 48 and Table 9 look at the realism of the portrayed network, the value of the AR DDG model, and the ability of the prototype to convey the relationship between the physical and logical layers of the network.



	Q1. How valuable would it be to use this type of system to visualize complex networks?	Q5. How valuable would it be to use this type of system to support collaborative decision-making?	Q6. How valuable was the AR visualization in enabling collaborative discussion when choosing between the different Courses of Action?
1 = Not Very Valuable	0	0	0
2 = Not Valuable	0	1	3
3 = Somewhat Not Valuable	0	0	3
4 = Neutral	0	1	3
5 = Somewhat Valuable	12	7	5
6 = Valuable	8	10	10
7 = Very Valuable	10	11	6

Figure 48. Prototype Value

Table 9. Prototype Value Statistics

	Q1. How valuable would it be to use this type of system to visualize complex networks?	Q5. How valuable would it be to use this type of system to support collaborative decision-making?	Q6. How valuable was the AR visualization in enabling collaborative discussion when choosing between the different Courses of Action?
Minimum	5	2	2
Maximum	7	7	7
Average	5.93	5.93	5.13
Standard Deviation	0.87	1.14	1.61

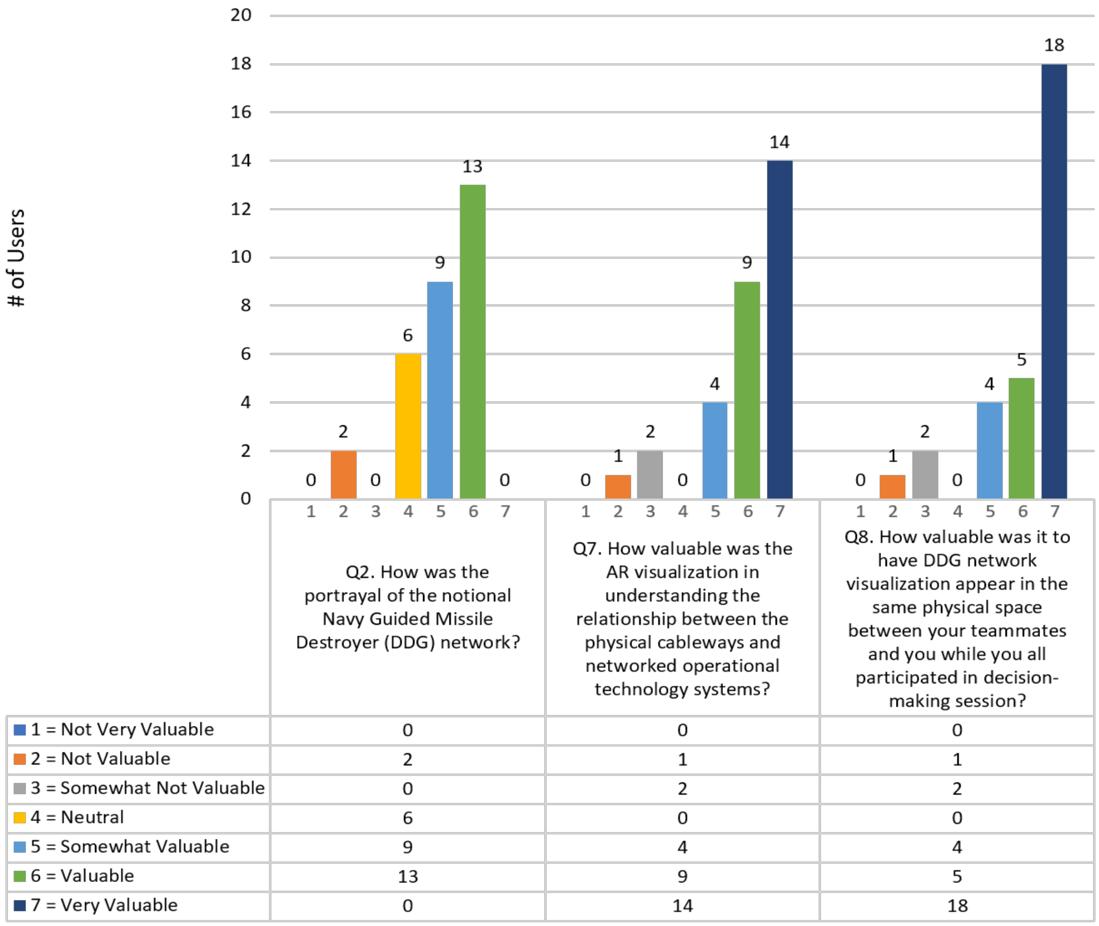


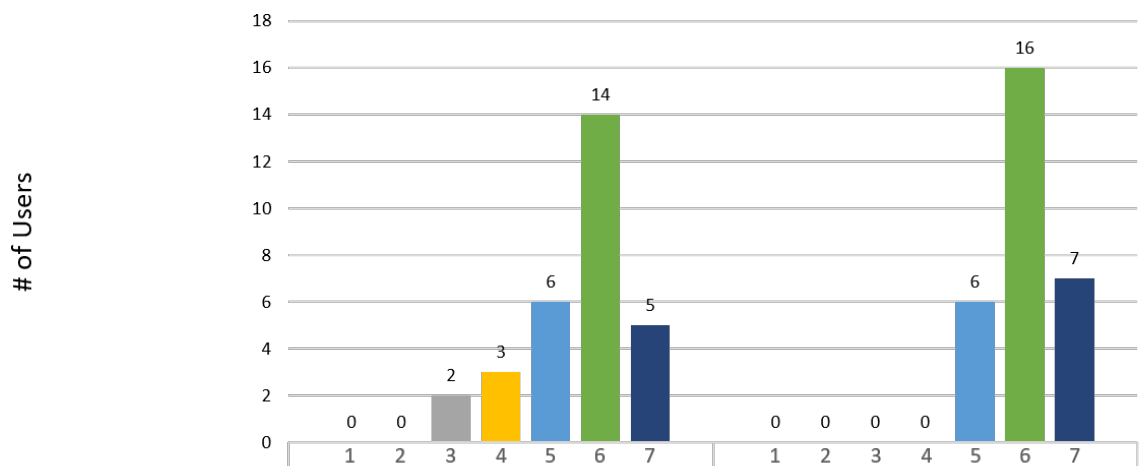
Figure 49. Value of Prototype Network Visualization

Table 10. Basic Statistical Analysis of the Value of Prototype Network Visualization

	Q2. How was the portrayal of the notional Navy guided missile destroyer (DDG) network?	Q7. How valuable was the AR visualization in understanding the relationship between the physical cableways and OT systems?	Q8. How valuable was it to have DDG network appear in the same space while in decision-making session?
Minimum	2	2	2
Maximum	6	7	7
Average	5.03	6.0	6.13
Standard Deviation	1.13	1.34	1.38

A vast majority of participants across the value-based questions found value in the prototype's ability to support collaborative visualization of complex networks and to enable a discussion about different COA's. The DDG network was deemed sufficiently accurate, and the AR portrayal of the network proved very supportive in understanding the physical-to-logical relationship of the network while promoting constructive communication between the team members.

Figure 50 and Table 11 discuss individual and team performance during the main scenario. Figure 51 and Table 12 examine the difficulty encountered in both communicating with other participants by utilizing the AR model, and navigating or interacting with the model.

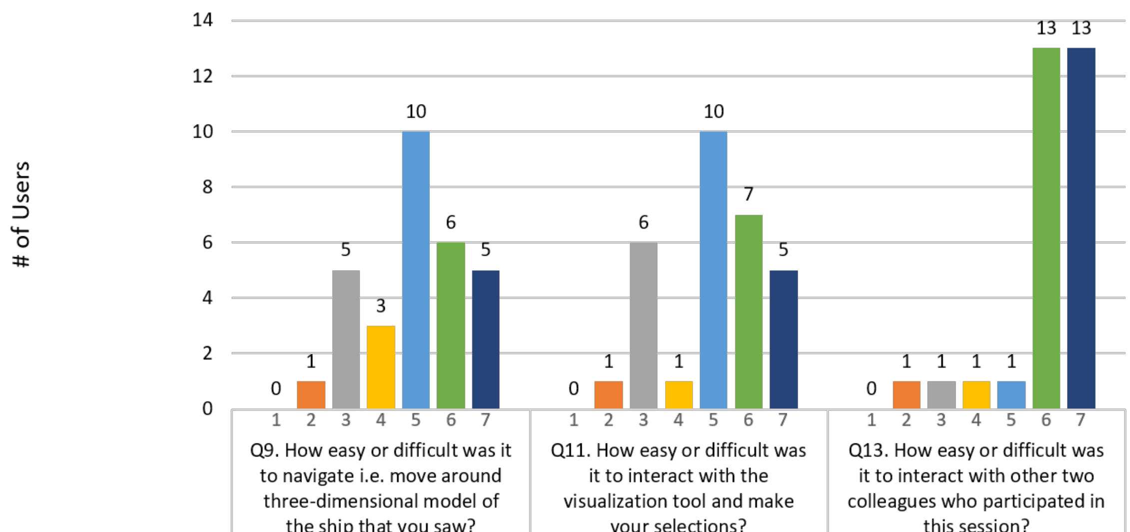


	Q4. How would you rate your own performance in this task?	Q15. How would you rate your team's performance in the scenarios you just completed?
1 = Strongly Dissatisfied	0	0
2 = Moderately Dissatisfied	0	0
3 = Somewhat Dissatisfied	2	0
4 = Neutral	3	0
5 = Slightly Satisfied	6	6
6 = Moderately Satisfied	14	16
7 = Strongly Satisfied	5	7

Figure 50. Participants' Performance with the Prototype

Table 11. Basic Statistical Analysis of Participants' Performance

	Q4. How would you rate your own performance in this task?	Q15. How would you rate your team's performance in the scenarios you just completed?
Minimum	3	5
Maximum	7	7
Average	5.57	6.03
Standard Deviation	1.10	0.68



	Q9. How easy or difficult was it to navigate i.e. move around three-dimensional model of the ship that you saw?	Q11. How easy or difficult was it to interact with the visualization tool and make your selections?	Q13. How easy or difficult was it to interact with other two colleagues who participated in this session?
1 = Very Difficult	0	0	0
2 = Difficult	1	1	1
3 = Somewhat Difficult	5	6	1
4 = Neutral	3	1	1
5 = Somewhat Easy	10	10	1
6 = Easy	6	7	13
7 = Very Easy	5	5	13

Figure 51. Reported Ease and Difficulty with the Prototype

Table 12. Basic Statistics for the Reported Ease and Difficulty with the Prototype

	Q9. How easy or difficult was it to navigate i.e., move around three-dimensional model of the ship that you saw?	Q11. How easy or difficult was it to interact with the visualization tool and make your selections?	Q13. How easy or difficult was it to interact with other two colleagues who participated in this session?
Minimum	2	2	2
Maximum	7	7	7
Average	5.0	5.03	6.10
Standard Deviation	1.41	1.45	1.21

Participants were, in general, very satisfied with both their personal performances and those of their team throughout the main scenario. We can only speculate that this is connected with the participants' ability to communicate through a difficult problem-solving scenario using the collaborative benefits of AR. It is noteworthy that approximately 20% of participants found it difficult to navigate the scenario or interact with the model during their session. This result may be a combination of an inherent learning hurdle encountered with Hololens hardware, as well as issues with the prototype itself; the latter could be easily remedied with extended participant testing and subsequent modifications of the prototype interface, perhaps even expanding the functionality of the resulting system.

Table 13 presents the results of fill-in-the-blank responses from participants in the post-task questionnaire. The responses to four questions were sorted in categories; equal or very similar responses were classified in the same categories (each category had to have responses from at least two participants).

Table 13. Qualitative Post-task Questionnaire Responses

Questions	Responses
Were there any issues when navigating around the three-dimensional model of the ship?	HUD Menu occupying workspace – **33%** No issues – **23%** Other – **20%** Laggy/choppy model when participant is moving – **17%** Fade plane makes model invisible from too far away – **7%**
What were the issues interacting with the visualization tool?	No issues – **50%** Ship system models were hard to select – **23%** Other – **17%** System status scroll menu not intuitive- **10%**
What were the issues interacting with other two colleagues who participated in this session?	No issues- **77%** Communication issues – **13%** Other – **10%**
What elements of your team's performance were done well?	No answer – **27%** Dividing roles/responsibilities – **67%** Other – **6%**
What elements of your team's performance were not done well?	No answer – **67%** Looking at the same systems/not communicating – **14%** Other – **12%** Decisions were hard without a designated leader – **7%**

Three main issues were encountered by participants during their time spent with our AR prototype. The first was the way the HUD option screen was displayed to the participant depending on the distance the person was from the DDG model. After some troubleshooting, we were able to replicate the situation: if a participant maximized the HUD while within 2ft of the DDG model, the HUD would take up over 80% of the viewable screen, thus, in essence, not allowing them the workspace needed to complete their COA scenario. The remedy was to exit and reenter the scenario, and to then open the HUD farther from the model. Although this proved to be a simple fix, the primary problem with the HUD resides in the original source code of the "tagalong" script attached to the HUD menu. It would be relatively simple to alter the script to look at the current distance the participant is from the model and scale the HUD appropriately.

The second issue encountered by many participants, some of whom did not write this on their questionnaire but discussed it between themselves during the scenario, was the FPS lag during the main scenario. Because the model contained more than one million polygons, the Hololens hardware had a difficult time processing and displaying the graphics fast-enough to satisfy the participants. The culprit to this issue resides in the size of the model and associated network objects as well as the completely integrated graphics processing suite in the Hololens software. Optimizing the model for Hololens use is a great option, but it would remove some of the specificity and authenticity of the network objects. An upgrade to the Hololens hardware would be another solution that would allow rendering more objects in the view of the participant without losing clarity or minimizing the complexity of the graphics.

The third issue noted by many participants was the size of the network objects they were selecting to determine the status of, and support COA development. This is easily remedied by increasing the size of the game objects in Unity, but it decreases the number of objects that could reside in a compartment at any given time. Another option that many participants did not try during the scenario was to just zoom the entire DDG model to allow for easier selection. We believe this was rarely done because participants were trying to be conscious of the other participants' view and did not think they were having identical problems.

The majority of issues brought up in the post-task questionnaire and during the usability test can be solved, but it will require time and additional usability testing.

G. BEHAVIORAL RESPONSES

We monitored (via video recording) the physical behavior cues of a total of 30 participants over ten 90-minute long sessions. The camera view encompassed the entire workspace and kept all participants in-view throughout the session. All participants stood for the entirety of the study; none of the participants showed any signs of dizziness or nausea, and none fell during the study.

The main observations noted while performing their tasks included the following:

1. The majority of participants used their outstretched hands to point out ship systems and network components they were discussing.

2. When given the option of using the Hololens clicker or hand gestures native to the Hololens, all participants began with the gestures, and very quickly transitioned to the clicker.

3. All groups eventually used the whiteboard to transcribe notes and compare the individual COA's during the scenario.

4. Participants were hesitant to use the model as a 3D object that one could walk around and interact with until they were prompted that it was possible to do so.

H. DISCUSSION

1. Limitations of Apparatus

The Microsoft Hololens has been instrumental in our research and usability study; however, there are inherent limitations to the hardware that need to be addressed. The most significant hardware issue with current version of this device is the narrow FOV that constantly cuts off 3D models. Unlike an immersive 360-degree VR headset with much larger horizontal and vertical FOV, the Hololens presents more of a 'window into AR." Having FOV of only 35°, the participants noted that they were not able to see the entire lengths of the objects. For example, our DDG model is, by nature, relatively long and narrow . If the Hololens had a larger FOV, the participants could see the entire model in their visual workspace instead having to constantly swivel their heads to peer into the workable AR space.

The second limitation of the Hololens is its GPU power. We only have one (albeit relatively complex) model, and we are not able to reach a constant frame rate of 60fps when actively interacting with it. Increasing the GPU power in such a small wireless form factor is not an easy, but the lag created by the sometimes-low frame rate directly impacted participant's visual experience, and presumably their task performance as well.

The last limitation of the Hololens noticed during the prototype build was the lack of native anchor sharing and networking. The Hololens toolkit gives developers the basic tools required to build a shared space that can be modified to allow multiple Hololenses. However, this either requires a network connection, or a LAN created specifically for a shared experience. A native application that allows multiple Hololenses to have a shared view of a model across a local area in addition to remote viewing in the same workspace would increase the potential use cases and open the development up to more research efforts and more domains.

2. Discussion of results

The objective and subjective data sets collected in the usability study, proved to be very useful in determining the potential value of our AR prototype.

As seen in Figures 38 and 39, frame rate fluctuations were constant throughout the study and changed more dramatically when participants moved toward and away from the model, or added complexity to the model through the addition of decks or network infrastructure. Participants in the study commented that these fluctuations in frame rate caused the strain on their eyes and that these fluctuations would temporarily impede their ability to accomplish the task at hand. In addition, we believe that the frame rate fluctuations hindered the participants from effectively communicating COA's and other concerns regarding the network visualized during the scenario. Although the frame rate instability most likely did affect the performance of the participants, it did not encumber them enough to prevent collaborative completion of their tasks.

The results from the SSQ show that our prototype did have a negative impact on the nausea-, oculomotor-, and disorientation-related sub-scores of participants. Although these symptoms were not explicitly called out by any participant during the study, the results suggest that more work to address those issues is needed; some of that work can be accomplished in future iterations of this prototype (e.g., reducing the size of the model, and making sure the frame rate is higher and constant), and some of the future work will require modifications to the Hololens hardware itself.

The SUS and Post-Task Questionnaire consistently established that our prototype was valuable in completing the collaborative network scenario presented during the usability study. There was general agreement that the prototype would be very beneficial for current complex network tasks. The general value of this tool comes not only from its ability to visualize the DDG network in AR, but also from the way in which it supports intuitive interaction with the model while promoting cyber SA and enabling collaboration between decision-makers.

VI. CONCLUSION AND FUTURE WORK

A. CONCLUSIONS

With the participation of 30 highly specialized subjects, nearly 20 hours of network-based task data, and hundreds of subjective data points, this study has provided valuable insights into the benefits and challenges associated with the use of AR in the context of shipboard systems. The results provided in Chapter V decisively suggest that a lightweight AR prototype system for a network operator or supervising officer would be beneficial in maximizing Cyber SA and allowing for increased collaborative decision-making. This chapter summarizes the many contributions that this work provides to the domains of AR, network visualization, and visualization research in general. Finally, this chapter suggests future of related research and prototyping, and similar efforts that can be accomplished in the military and civilian AR domains. The chapter lays out direction for the continued work, and it recommends ideas for future implementation of AR visualizations onboard USN vessels.

B. DOMAIN CONTRIBUTIONS

The research completed in this study contributes to several domains. First in the domain of military research, we have provided empirical evidence of the potential and value of visualizing USN vessel networks with a wireless, low-cost, COTS AR device. The ability to visualize operational systems in a complex OT environment such as a USN destroyer is a substantial improvement over paper diagrams. Our hypothesis regarding the possibility of building an AR network visualization tool using COTS technology, was completely validated. We also believe this prototype assists operators and managers in their network tasks, cyber SA, and decision-making. The objective data set collected in the study identified several difficulties with the software and hardware that will need to be addressed; this is especially the case if future versions of the prototype are required to function in high-stress operational scenarios such as an equipment casualty. The subjective data set shows a great potential for and increased user satisfaction with a new way of visualizing networks in complex environments. We believe that our prototype is a good first step towards a more general solution.

In the domain of network research, our prototype has demonstrated that, even without built-in collaborative networking for the Hololens, it is possible to accurately represent a complex network, and allow the interaction of multiple users in the same local workspace. The resulting prototype allows the pursuit of further research focused on dynamic visualization of OT networks and their subsystems, including their operational and non-operational statuses.

In the AR domain, we have taken a novel concept for visualizing networks, and assembled it into a working prototype that supported intuitive interaction with the model and team collaboration. AR is not new technology for the military, or even for the Navy, but our collaborative visualization concept is, and our research could enable burgeoning visualization designs for SCADA networks, or any other complex industrial control systems. This work also contributes to the field by precisely detailing the build process, as well as software and hardware needed to replicate our visualization on upgraded AR hardware in the future.

C. FUTURE WORK

This study was designed to test the usability of an AR network visualization prototype for network operators, their supervisors, and leadership. The most applicable future work would be to integrate damage control, the ships electrical system and waste management to support visualizing mass equipment casualties and promote quick decision-making in times of operational necessity. The majority of the positive feedback received from this study recommended the full-scale application of AR to modeling and visualizing ship systems holistically. To accomplish this, all connected systems would need to be modeled both physically and logically. The resulting visualization tools would enable better situational awareness when the operations of one system dynamically effects the operations of other dependent or interacting systems.

On a more focused network-level, adding real-time network management to our prototype would allow the system to update system statuses. This is already achieved in many complex SCADA networks, and is used for damage control nodes in many USN vessels For example the prototype might be augmented so that should a network component such a switch become inoperable, a simple query to a specific port could give real-time information to the server, which would then send a custom message to the attached Hololenses, turning that node red and updating its status log. This upgrade would remove the requirement for a technician to manually change the status of each node and positions the AR system to be much more self-sufficient. Also, being able to add nodes or make edits to the network components within the AR system would allow for quick edits or COA changes. Having to rebuild onto the Hololens for each change to the model is a laborious process and would not be necessary with this addition.

Further extend the current research, a comparative analysis of the AR system of visualizing networks against the traditional paper methods would be valuable. This work would entail building complex networks using both AR and paper methods, and quantitatively and qualitatively comparing them. Factors such as performance, physical space required to work, and accuracy could be evaluated.

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APPENDIX A. RECRUITMENT FLYER

Experience Visualization of Computer Networks with Augmented Reality (AR)

Help a fellow student's thesis research to understand the feasibility of using commercial off the shelf augmented reality technology to visualize computer networks with Augmented Reality (AR) technology. You will be using an AR headset to visualize a notional Navy guided missile destroyer (DDG) network. At the end you will be asked to provide feedback via questionnaire.

WHAT: You will be asked to make operational decisions based on a notional Navy DDG network infrastructure

WHY: Help us study visualization of computer networks with AR technology

WHO: NPS Navy students

WHERE: Watkins Hall, Room 212A

LENGTH: About 60 min

SCHEDULE: Sign up at http://signup.com/go/WLwarBv

CONTACTS: Student: Matthew Timmerman mrtimmer@nps.edu
Principal investigator: Dr. Amela Sadagic asadagic@nps.edu
IRB Chair: Dr. Larry Shattuck lgshattu@nps.edu

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APPENDIX B. DEMOGRAPHIC QUESTIONNAIRE

1. Year of Birth: ______
2. Years of Service: ______
3. Current Rank: _______________________________
4. Functional Area/Specialty: ____
5. Have you ever administratively/operationally managed a network before?

   YES NO

6. If 'YES' For how long? ________ years.
7. Have you ever influenced network operations decision-making?

   YES NO

8. If 'YES':
   a) When did the decision-making occur? ___________ (year)
   b) What aspects of that network visualization did you value most (what it allowed you to do)?

   ____

   c) What aspects of that network visualization could be improved or changed (what it did not allow you to do)?

   ____

9. What hand do you use to operate a computer mouse? Select one answer.

   Left Right I'm god with either

10. Do you play video games?

    YES NO

11. If "YES":
    a. How often? (select one that applies)

       ___ Less than 2 hrs/wk
       ___ 2–4 hrs/wk
       ___ 4–8 hrs/wk
       ___ More than 8 hrs/wk

b. What percentage of game types do you play? Ensure that both values add to 100%.

single-player ______ % multi-player ______ %

12. Have you use used virtual reality or augmented reality head mounted displays before?

YES NO

13. If 'YES':

a. What kind? (select all that apply)

___ HTC Vive
___ Oculus Rift
___ Oculus Go
___ Gear VR
___ Google Cardboard style
___ Hololens
___ Other: ____

b. How many times in last 5 years? (select one that applies)

___ Only once
___ Less than 5 times
___ Between 5 and 10 times
___ More than 10 times

c. When was the last time you used it? (select one that applies)

___ Within last 30 days
___ Within last 6 months
___ Within the last year
___ More than a year ago

APPENDIX C. SUS QUESTIONNAIRE

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

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APPENDIX D. POST-TASK QUESTIONNAIRE

1. How valuable would it be to use this type of system to visualize complex networks? Select one answer.

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

2. How was the portrayal of the notional Navy guided missile destroyer (DDG) network?

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

3. How was your overall experience with the task you were asked to do?

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

4. How would you rate your own performance in this task?

1	2	3	4	5	6	7
Strongly dissatisfied	Moderately dissatisfied	Somewhat dissatisfied	Neutral	Slightly satisfied	Moderately satisfied	Strongly satisfied

5. How valuable would it be to use this type of system to support collaborative decision-making? Select one answer.

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

6. How valuable was the AR visualization in enabling collaborative discussion when choosing between the different Courses of Action? Select one answer.

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

7. How valuable was the AR visualization in understanding the relationship between the physical cableways and networked operational technology systems? Select one answer.

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

8. How valuable was it to have DDG network visualization appear in the same physical space between your teammates and you while you all participated in decision-making session? Select one answer.

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

9. How easy or difficult was it to navigate i.e., move around three-dimensional model of the ship that you saw? Select one answer.

1	2	3	4	5	6	7
Very difficult	Difficult	Somewhat difficult	Neutral	Somewhat easy	Easy	Very Easy

10. If there was any issue in navigating i.e., moving around three-dimensional model of the ship, please explain what they were:

    a. ______________________________
    b. ______________________________
    c. ______________________________

11. How easy or difficult was it to interact with the visualization tool and make your selections? Select one answer.

1	2	3	4	5	6	7
Very difficult	Difficult	Somewhat difficult	Neutral	Somewhat easy	Easy	Very Easy

12. If there was any issue in interacting with the visualization tool that you experienced, please explain what they were:

    a. ______________________________
    b. ______________________________
    c. ______________________________

13. How easy or difficult was it to interact with other two colleagues who participated in this session? Select one answer.

1	2	3	4	5	6	7
Very difficult	Difficult	Somewhat difficult	Neutral	Somewhat easy	Easy	Very Easy

14. If there was any issue in interacting with other two colleagues who participated in this session, please explain what they were:

    a. ______________________________
    b. ______________________________
    c. ______________________________

15. How would you rate your team's performance in the scenarios you just completed? Select one answer.

1	2	3	4	5	6	7
Not very successful	Not successful	Somewhat not successful	Neutral	Somewhat successful	Successful	Very successful

16. What elements of your team's performance were done well?

    a. ______________________________
    b. ______________________________
    c. ______________________________

17. What elements of your team's performance were not done well?

a. ____

b. ____

c. ____

18. Additional Comments/Remarks:

____

____

____

____

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APPENDIX E. SIMULATOR SICKNESS QUESTIONNAIRE

Instructions : Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. « Fullness of the Head »	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

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APPENDIX F. INFORMED CONSENT FORM

Naval Postgraduate School
Consent to Participate in Research

Introduction. You are invited to participate in a research study entitled 'Visualization of Computer Networks with Augmented Reality System'. The purpose of the research is to determine suitability of using AR technology for visualization of computer networks.

Procedures. You will be asked to complete a network-based task focused on collaboratively choosing an appropriate Course of Action (COA) based on a given scenario. After reviewing scenario and current network status documents, you and two other subjects will use the Augmented Reality (AR) system and execute a task given by the experimenter. You will be asked to complete a brief survey at the end of your task. The full duration of your participation should last approximately 60 minutes. The expected number of individuals who will have the opportunity to participate in this research study will not exceed 45.

Video Recording. Video recording will be taken of all participants during collaborative tasks as part of the research study to determine usability of the prototype. Recordings gathered will not be used for any other purpose.

Location. The study will take place Watkins Hall Room 212A.

Cost. There is no cost to participate in this research study.

Voluntary Nature of the Study. Your participation in this study is strictly voluntary. If you choose to participate you can change your mind at any time and withdraw from the study. You will not be penalized in any way or lose any benefits to which you would otherwise be entitled if you choose not to participate in this study or to withdraw. The alternative to participating in the research is to not participate in the research.

Potential Risks and Discomforts. Symptoms of cyber sickness can occur with exposure to immersive virtual environment; they are similar to motion sickness symptoms. While every effort in the design of the virtual environment testing platform has been made to mitigate cyber sickness, there is a possibility the subject may have symptoms present during the study. Symptoms include visual symptoms (eyestrains, blurred vision, headaches), disorientation (vertigo, imbalance) and nausea (vomiting, dizziness). If symptoms are observed by the experimenter or participants remark upon feeling any of these symptoms, participants will be removed from the study. Additionally, participants are at risk of breach of confidentiality.

Anticipated Benefits. This study with advance our understanding of the role that commercial off the shelf augmented reality systems in visualizing computer networks. You will not directly benefit from your participation in this research.

Compensation for Participation. No tangible compensation will be given.
Confidentiality & Privacy Act. Any information that is obtained during this study will be kept confidential to the full extent permitted by law. All efforts, within reason, will be made to keep

your personal information in your research record confidential but total confidentiality cannot be guaranteed. Survey data will be kept only on NPS approved and owned data systems. All survey data will only identify you by Subject ID that is different from your name. Only the researcher and principal investigator will have access to the collected data for analysis. The data will be stored in a secured document and the principal investigator will maintain all electronic data upon completion of the study for 10 years.

Points of Contact. If you have any questions or comments about the research, or you experience an injury or have questions about any discomforts that you experience while taking part in this study please contact the Principal Investigator, *Dr. Amela Sadagic at (831) 656–3819* or asadagic@nps.edu. Questions about your rights as a research subject or any other concerns may be addressed to the Navy Postgraduate School IRB Chair, Dr. Larry Shattuck, 831–656-2473, lgshattu@nps.edu.

Statement of Consent. I have read the information provided above. I have been given the opportunity to ask questions and all the questions have been answered to my satisfaction. I have been provided a copy of this form for my records and I agree to participate in this study. I understand that by agreeing to participate in this research and signing this form, I do not waive any of my legal rights.

______________________________________	___________________
Participant's Signature	Date

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