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THESIS

**SUPPORTING COMBINED ARMS MILITARY
DECISION-MAKING PROCESS WITH AR TECHNOLOGY**

by

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June 2023

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**SUPPORTING COMBINED ARMS MILITARY DECISION-MAKING PROCESS
WITH AR TECHNOLOGY**

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ABSTRACT

The military decision-making process (MDMP) involves the critical task of analyzing the terrain to ensure mission success. However, traditional terrain analysis methods, such as two-dimensional (2D) analog maps, PowerPoint presentations, and mission command systems, are resource-intensive, time-consuming, and can confuse decision-makers. Therefore, this research focused on the use of the mobile, head-mounted augmented reality (AR) display technology for three-dimensional (3D) terrain visualization to address these challenges. AR technology lets users observe virtual objects superimposed onto their physical surroundings, yielding an enhanced immersive experience. The tool allows users to view and manipulate the terrain in 3D, add representations of military resources, examine the resulting configuration, and engage in MDMP. The usability study assessed the effectiveness, efficiency, and user satisfaction with the interface, focusing on 3D visualization tasks, extraction of derivative terrain information, and unit placements in a contested wet gap crossing scenario. The results showed that the AR terrain visualization prototype provided decision-makers with more comprehensive and accurate information, leading to successful mission planning and execution. This research highlights the potential of 3D terrain visualization and AR technology to improve the MDMP, provide decision-makers with a better understanding of the environment, and enable them to make more informed decisions.

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TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	RESEARCH DOMAIN	1
B.	PROBLEM AND MOTIVATION.....	1
C.	RESEARCH QUESTIONS	3
D.	SCOPE	4
E.	METHODOLOGY	4
F.	THESIS STRUCTURE	5
II.	BACKGROUND AND LITERATURE REVIEW	7
A.	INTRODUCTION.....	7
B.	VIRTUAL REALITY AND AUGMENTED REALITY.....	7
1.	Augmented Reality.....	7
2.	Virtual Reality	10
3.	Reality-Virtuality Continuum.....	11
4.	Low-Cost Commercial-Off-the-Shelf Solutions	12
C.	EFFECTIVENESS OF AR FOR SMALL TEAM COLLABORATION IN MILITARY OPERATIONS.....	17
D.	AUGMENTED REALITY SANDTABLE (ARES).....	20
1.	Intent and Design	20
2.	How ARES Works	21
3.	ARES Advantages and Disadvantages.....	22
4.	Analysis of ARES Performance.....	23
E.	CHAPTER SUMMARY.....	23
III.	TASK ANALYSIS: CURRENT MDMP PRACTICES	25
A.	INTRODUCTION	25
B.	ARMY DESIGN METHODOLOGY FOR PLANNING (ADM).....	25
C.	MILITARY DECISION-MAKING PROCESS	26
D.	TASK OBJECTIVE, STAFF, STEPS, AND TOOLS	28
E.	INFORMATION PREPARATION OF THE BATTLEFIELD.....	31
F.	CURRENT USE AND LIMITATIONS OF 2D MAPS AND INTELLIGENCE PRODUCTS.....	33
G.	STAFF COLLABORATION DURING MDMP	36
H.	STAFF RECOMMENDATION TO A COMMANDER.....	38
I.	GAPS IN CURRENT PRACTICES OF MDMP	40
J.	CHAPTER SUMMARY.....	41

IV.	PROTOTYPE SYSTEM DESIGN AND IMPLEMENTATION.....	43
A.	INTRODUCTION.....	43
B.	FRAMEWORK.....	43
	1. Why AR?.....	43
	2. Why Microsoft HoloLens?	44
	3. Why Unity and Microsoft Visual Studio?.....	44
	4. Hardware	45
C.	SIMULATION ENVIRONMENT	46
	1. System Architecture and Initial Design	46
	2. Microsoft Holographic Remoting Application.....	46
	3. MRTK Mixed Reality Tool Kit.....	47
D.	3D MODELS AND TERRAIN	48
	1. Height Maps for Virtual Terrain.....	48
	2. Building 3D Terrain.....	50
E.	GRID COORDINATE SYSTEM	51
F.	HEADS-UP DISPLAY (HUD) INFORMATION PANELS	53
	1. Control Panel.....	54
	2. Terrain Information GUI.....	61
	3. Taskbar GUI.....	62
G.	TASK USER INTERFACE	63
H.	CHAPTER SUMMARY.....	63
V.	USABILITY STUDY	65
A.	INTRODUCTION.....	65
B.	INSTITUTIONAL REVIEW BOARD (IRB) PROCESS.....	65
C.	STUDY DESIGN.....	66
	1. Physical Environment.....	66
	2. Training Environment.....	67
	3. Terrain Visualization Tasks.....	68
	4. Collection of Objective Data Set.....	69
	5. Collection of Subjective Data Set.....	70
D.	PROCEDURE	71
E.	PARTICIPANTS.....	72
	1. Demographics Questionnaire.....	72
	2. Demographics Questionnaire: Experience	74
F.	RESULTS	76
	1. Objective Data Set.....	76
	2. Subjective Data Set	84
G.	CHAPTER SUMMARY.....	98

VI. CONCLUSION AND FUTURE WORK	99
A. CONCLUSION	99
B. DOMAIN CONTRIBUTIONS	99
C. FUTURE WORK.....	100
APPENDIX A. GRIDCELL.....	103
APPENDIX B. GRIDINTERACT.....	105
APPENDIX C. GRIDLABELS.....	109
APPENDIX D. RECRUITMENT FLYER.....	111
APPENDIX E. SIMULATOR SICKNESS QUESTIONNAIRE.....	113
APPENDIX F. SYSTEM USABILITY SCALE.....	115
APPENDIX G. DEMOGRAPHICS.....	117
APPENDIX H. POST-TASK QUESTIONNAIRE	119
LIST OF REFERENCES.....	127
INITIAL DISTRIBUTION LIST	133

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LIST OF FIGURES

Figure 1.	Image generation for augmented reality displays. Source: Bimber and Raskar (2005).	8
Figure 2.	Head-mounted device. Source: Turner and Cruz (2022).	9
Figure 3.	Hand-held augmented reality display. Source: Greunke (2015).	9
Figure 4.	Virtual sand table, behavior analysis and synthesis for intelligent training project. Source: Sadagic et al. (2013).	10
Figure 5.	VR and the transformation of medical education. Source: Pottle (2019).	11
Figure 6.	VR continuum. Source: Milgram and Kishino (1994).	12
Figure 7.	Six degrees of freedom. Source: GregorDS (2015).	13
Figure 8.	Meta Quest 2.	15
Figure 9.	HoloLens 2.	15
Figure 10.	HoloLens 2 flipped-up.	16
Figure 11.	Augmented reality utilization in military operations. Source: Slyusar (2021).	18
Figure 12.	Augmented reality sand table: Terrain recognition process. Source: Amburn et al. (2015).	21
Figure 13.	ARL’s ARES. Source: DignitasTechnologies (2015).	22
Figure 14.	Frame the operational environment. Source: Headquarters, Department of the Army (2019).	26
Figure 15.	Military decision-making process. Source: Headquarters, Department of the Army (2014).	27
Figure 16.	Decision-support matrix. Source: Klein and Hasting (2016).	30
Figure 17.	IPB product outputs. Source: Lobdell (2019).	32
Figure 18.	Products of the IPB process. Source: Headquarters, Department of the Army (2019).	34

Figure 19.	Optimizing 2D and 3D visualization. Source Dübel et al. (2014).	35
Figure 20.	MDMP planning. Source: U.S. Army Combined Arms Center (2016).	37
Figure 21.	1st Calvary Division situation template. Source: Schoenfeldt and Stalling (2021).	39
Figure 22.	Components of simulation. Source: Turner and Cruz (2022).	46
Figure 23.	Hand tracking sensors. Source: Hand Tracking—MRTK 2 (2022).	47
Figure 24.	Height map example. Source: Skydark (2022).	49
Figure 25.	Exporting height map into Unity. Source: Skydark (2022).	50
Figure 26.	Virtual terrain when viewed through Unity.	51
Figure 27.	Gaze-tracking and pinching gesture to acquire a grid.	52
Figure 28.	Grid coordinates displayed in HL2.	53
Figure 29.	Control panel.	54
Figure 30.	Rotate map component.	56
Figure 31.	Military unit components.	57
Figure 32.	Infantry unit six battle positions.	58
Figure 33.	Artillery unit three PAAs	59
Figure 34.	Engineer unit three river crossing sites.	60
Figure 35.	Enemy unit component.	60
Figure 36.	Terrain information GUI for a single (pinch).	61
Figure 37.	Terrain information GUI for hold the (pinch) between two points.	62
Figure 38.	Taskbar example.	62
Figure 39.	View of training area without HL2 headset.	67
Figure 40.	The H-Tips application.	68
Figure 41.	Ray-Casting and selecting an object in H-Tips.	68

Figure 42.	An example of the event log	70
Figure 43.	Participants’ current military rank (Demographics questionnaire, Question 3).....	73
Figure 44.	Branch of service (Demographics questionnaire, Question 6).	74
Figure 45.	Prior participation in military planning process (Demographics questionnaire, Question 14).	75
Figure 46.	Previous use of AR or VR HMD (Demographics questionnaire, Question 11).....	76
Figure 47.	Participants’ average time for the eight tasks in the VE.....	77
Figure 48.	Average number of attempts for Task 1 and 2.....	78
Figure 49.	Number of additional attempts to complete task 3.	79
Figure 50.	Number of additional attempts to complete task 4.	80
Figure 51.	Number of additional attempts to complete task 5.	81
Figure 52.	Number of additional attempts to complete task 6.	82
Figure 53.	Number of additional attempts to complete task 7.	83
Figure 54.	Number of attempts to complete task 8.	84
Figure 55.	After training session SSQ-1 values	86
Figure 56.	After training session SSQ-2 values	87
Figure 57.	System usability scale.....	90
Figure 58.	Ease of use rating.....	93
Figure 59.	Effectiveness rating.....	94
Figure 60.	Satisfaction rating for Tasks 1–3.	97
Figure 61.	Satisfaction rating for Tasks 4–8.	98

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LIST OF TABLES

Table 1.	Participants' gender (Demographics questionnaire, Question 5).	73
Table 2.	Years of service.....	74
Table 3.	Number of attempts to transform terrain.	79
Table 4.	Number of attempts to evaluate battle positions and place an infantry unit.	80
Table 5.	Number of attempts to evaluate PAA and place an artillery unit.	80
Table 6.	Number of attempts to evaluate a crossing site and place an engineer unit.	81
Table 7.	Number of attempts to evaluate enemy positions.	82
Table 8.	Number of attempts to evaluate a wet gap crossing.	83
Table 9.	SSQ overall scores	85
Table 10.	SUS questionnaire: frequency of participants' responses.....	88
Table 11.	SUS questionnaire: participants' response analysis.....	89

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
ADM	Army Design Methodology
AO	area of operation
AR	augmented reality
ARES	augmented reality sand table
COA	course of action
COP	common operating picture
COTS	commercial off the shelf
GUI	graphical user interface
HHD	handheld display
HMD	head mounted display
HUD	heads up display
IPB	intelligence preparation of the battlefield
MDMP	military decision making process
MRTK	Mixed Reality Tool Kit
OPORD	operation order
PAA	Position Artillery Area
SD	spatial display
VE	virtual environment
VR	virtual reality
WFF	warfighting function
WGC	wet gap crossing

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EXECUTIVE SUMMARY

The military decision-making process is a critical aspect of military operations, and the ability to analyze terrain is essential for successful mission planning and execution. However, analyzing terrain has remained relatively unchanged for many years and can be resource intensive. In addition, the process involves collaboration among multiple staff sections, each using different tools and methods to analyze the terrain, which can lead to confusion and difficulty for decision-makers.

To improve the process of analyzing terrain, I explored the use of three-dimensional (3D) terrain visualization and mobile, head-mounted augmented reality (AR) display technology to extract terrain information critical for military decision-making. That type of AR technology allows users to overlay virtual objects in the real world, providing a more realistic and immersive experience.

The AR terrain visualization prototype was designed and developed to evaluate the feasibility of this approach, test the overarching concepts, and examine the usability of the resulting user interface. The prototype allowed users to view and manipulate the terrain in 3D, add representations of military resources, examine the resulting configuration, and engage in MDMP; the tool provided a more detailed, interactive experience than traditional static two-dimensional (2D) maps or PowerPoint presentations. I then conducted usability tests to assess the prototype's interface's effectiveness and identify improvement areas.

Additionally, I conducted a study to assess users' comprehension of completing 3D visualization tasks, focusing on extracting derivative terrain information and unit placement in a contested wet gap crossing scenario. The study involved using the AR terrain visualization prototype and AR headset to simulate a wet gap crossing scenario, where users had to make decisions based on the terrain's features and the location of the enemy forces. The study's results provide insights into the effectiveness of AR technology for supporting decision-making in complex military scenarios.

Overall, my research highlights the potential of AR technology for improving the Military Decision-Making Process and providing decision-makers with more

comprehensive and accurate information. With the creation of an interactive 3D terrain visualization tool, decision-makers could better understand the environment and make more informed decisions, leading to successful mission planning and execution.

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I. INTRODUCTION

A. RESEARCH DOMAIN

This research focuses on utilizing augmented reality (AR) technology to support Military Decision-Making Process (MDMP), a crucial aspect of mission planning. The tool enables a user's interaction with native three-dimensional (3D) data sets that describe terrain and allows the use of a set of 3D tools. As a result, the tool has the potential to enhance decision-making processes and make MDMP sessions more effective.

Traditionally, the United States (U.S.) Army has relied on two-dimensional (2D) graphical information when planning missions. However, acquiring more detailed information about the terrain requires significant time and resources, such as creating additional 2D graphical representations. By contrast, if the terrain is already captured and represented as a 3D data set, the staff members will have all the necessary information to engage in MDMP and make better-informed decisions.

The thesis research includes a design and development of an augmented reality (AR) visualization tool that operates with 3D virtual terrains and supports MDMP, particularly emphasizing mission planning for a wet gap crossing (WGC). The thesis aims to improve staff collaboration during MDMP by furnishing precise data on virtual terrain, allowing the use of 3D tools, and enabling better decision-making. Additionally, this study enhances the comprehension of the technological prerequisites needed to facilitate small-team cooperation in MDMP.

B. PROBLEM AND MOTIVATION

Technological advancements often surpass their adoption and integration into existing systems and processes, which is a common occurrence. For instance, using AR and virtual reality (VR) technologies for information sharing in military missions can significantly improve the planning and execution of complex and dynamic operations. However, incorporating these technologies into existing mission command systems and procedures can be challenging and time-consuming, mainly because of military operations'

security and reliability requirements. Additionally, users may be resistant to the introduction of novel solutions and technologies they are not familiar with. As a result, despite the rapid progress made in information-sharing technology, its integration into the military sector is progressing at a much slower rate. Consequently, complex, and ever-changing military operations are still being planned and executed using outdated protocols and with only slight improvements to mission command systems over prolonged periods.

The U.S. Army uses various methods to extract information and analyze the terrain during MDMP. Predominately, each of the Army's warfighting functions extracts terrain information using 2D maps; the staff sections request information through the Intelligence Topography Section for more detailed information. Staff sections then take the information gathered from 2D maps and information provided by the Intelligence Section and make a PowerPoint presentation. A commander uses that set to make the final decision. However, because of the inherent limitations of 2D maps and the form they are represented (static 2D maps presented in PowerPoint slides), staff sections cannot always extract derivative information from the terrain to make well informed decisions. Having the terrain represented in native 3D data format and access to a range of suitable 3D tools, would allow the staff members to extract derivative information from the terrain, increase collaboration, and enable an improved understanding of the common operating picture (COP).

AR in the military domain is not new; however, the technology has not been extensively utilized during MDMP. By using the AR visualization tool during MDMP, staff members may have system capabilities previously unavailable for their work and collaboration. Displaying and interacting with 3D virtual terrain in AR allows each WWF to use simple hand gestures to navigate around the terrain, manipulate those data sets, maneuver and zoom in and out of the terrain, and extract derivative information needed for their decision-making. As a result, WWFs can substantiate their decisions with a thorough understanding of the terrain specifics and provide a much better articulation of why they recommend a specific COA to a commander. Additionally, the errors that may arise from misunderstanding the 2D data sets may be reduced, if not even eliminated.

There is a good reason why focusing on WGC represents a fertile ground for deploying AR technology and using 3D data representation. A WGC is one of the most challenging combined arms missions for the U.S. Army personnel; planning this type of mission is highly complex because of the extensive resources and human capital needed to be engaged (U.S. Army Combined Arms Center, 2019). Six WFFs within the U.S. Army must seamlessly orchestrate their efforts for the safe conduct of a WGC. At the start of MDMP, each of the U.S. Army's WFFs is briefed by the Intelligence Sections on terrain analysis; this phase is called Intelligence Preparation of the Battlefield (IPB). The IPB represents a high-level look at the terrain within a unit's area of operation (AO), and it provides historical data on terrain expectations (Headquarters, Department of the Army, 2019); most of their decisions are based using 2D maps. After IPB is conducted, WFFs develop courses of action (COAs) based on information provided by the Intelligence Section. However, the reliance on 2D maps has many inherent limitations. For example, the terrain cannot be viewed from any given point (the data set is not recorded in 3D), thus missing the richness of terrain information needed for a productive MDMP. Thus, using a superior data representation that minimizes the possibility of making errors and investing time productively to examine alternatives and decision-making has the potential to bring much-needed improvements and strategic advantage to such complex military operations.

C. RESEARCH QUESTIONS

This thesis addresses the following research questions:

1. What is the technological framework that has the potential to provide the most effective support for Combined Arms MDMP?
2. Can AR-supported MDMP tool enhance Warfighting Functions' understanding of terrain by providing derivative information on terrain analysis?
3. Can the AR-supported MDMP tool effectively assist with resource management?

4. Can the AR-supported MDMP tool effectively assist military staff collaboration in combined arms scenarios?

D. SCOPE

This thesis is limited to developing an AR visualization tool and virtual environment that supports “wet gap crossing” and extracting derivative information about the terrain each WWF needs during MDMP. In addition, the same tool can enable staff collaboration and information exchange between military staff sections.

E. METHODOLOGY

The methodology that is used to address all research questions includes the following steps:

1. Literature review: Conduct a literature review and provide background information about the essential constructs used in the thesis.
2. Task Analysis: Execute analysis of current practices of conducting MDMP for wet gap crossing. That includes but is not limited to detailed analysis of reporting and interactions between different Warfighting Functions during Course of Action Development, current terrain visualization practices, and team collaboration.
3. Design of the AR-visualization tool: Design supporting system architecture for the tool and user interface. Additionally, select a set of 3D objects and terrain needed to support user tasks.
4. Usability Study: Conduct a usability study focused on the functionality and performance of the AR-supported MDMP tool.
5. Data analysis: Analyze a comprehensive data sets collected during usability study.
6. Derive conclusions and propose future work.

F. THESIS STRUCTURE

Chapter I: Introduction. This chapter introduces the most critical elements of the research space: domain, problem, research questions, scope, and methodology used to address all research questions.

Chapter II: Background and Literature Review. This chapter discusses how the U.S. Army conducts ADM and MDMP for planning military operations. The chapter also discusses past and current uses of VR and AR and potential uses of AR when military staff members collaborate during the MDMP process.

Chapter III: Task Analysis: Current MDMP Practices. This chapter analyzes the current practices and tools that Army staff personnel use for analyzing terrain during MDMP and how COA is recommended to a commanding officer. Additionally, this chapter discusses knowledge gaps when information is presented to a commander in 2D.

Chapter IV: Prototype System Design and Implementation. This chapter discusses the design and development of the AR visualization tool, the system architecture, the user interface, and the simulation environment. The text also describes the WGC scenario and the 3D models built for a virtual environment required for the usability study.

Chapter V: Usability Study. This chapter discusses the methodology for conducting a usability study using an AR visualization tool, including the development of the full Institutional Review Board documentation. Additionally, the text discusses the virtual environment, technology requirements, and the objective and subjective data sets collected in usability study. Finally, this chapter analyzes the results of the usability study.

Chapter VI: Conclusion and Future Work. This chapter outlines the main points from the study and provides recommendations for future work.

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II. BACKGROUND AND LITERATURE REVIEW

A. INTRODUCTION

This chapter introduces fundamental concepts and a literature review of the research domain discussed in this thesis. The topics discussed throughout this chapter elaborate on the use of AR and VR to support different user needs. This chapter also discusses different low-cost commercial-off-the-shelf (COTS) solutions and their use for training situations and small team collaboration.

B. VIRTUAL REALITY AND AUGMENTED REALITY

1. Augmented Reality

Ron Azuma proposed a definition of AR that is the most frequently used by researchers in the AR scientific community. He defined AR as a type of virtual environment (VE) where the virtual digital elements are superimposed over the visual sensory information that corresponds to the actual (physical) world. In other words, instead of replacing reality, Azuma says that AR enhances it (Azuma, 1997). If everything were ideal, the user's perception would be that physical and digital objects coexist seamlessly. Furthermore, Azuma's statement also describes how AR systems combine virtual and real elements and allow for real-time user interactions and 3D registration (Azuma, 1997). Figure 1 is an example of image generation using AR technology.

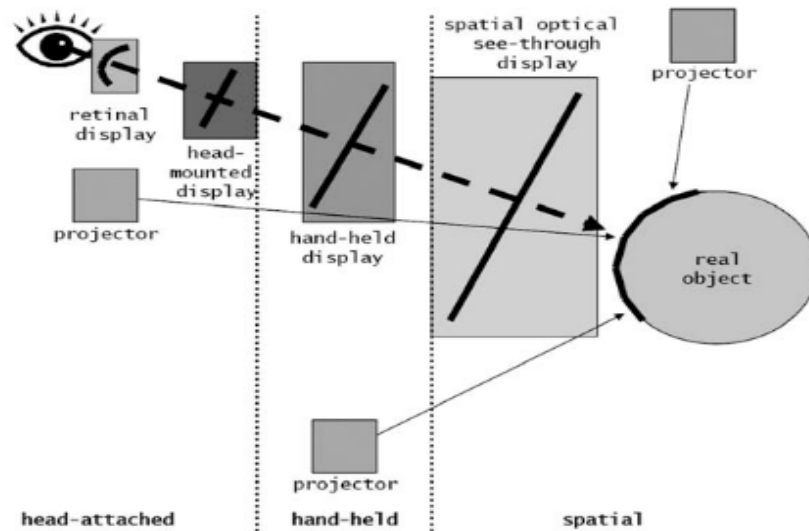


Figure 1. Image generation for augmented reality displays. Source: Bimber and Raskar (2005).

AR technology has numerous display options. When discussing the usage of augmented reality technology, Bimber and Raskar suggest that even a laptop with a built-in webcam may offer AR experiences by just superimposing virtual things on the actual world (Bimber & Raskar, 2005). Bimber and Raskar classified AR visual displays into three groups: head-attached displays (HMD), hand-held displays (HHD), and spatial displays (SD). Since HMDs enable many mobile applications and can deliver high fidelity of rendered virtual objects and allow for hands-free interaction, those visual displays are the dominating technology within the industrial sector. HHDs, being highly mobile and already owned by many potential users like mobile phones and tablets, offer a suitable substitute for the head-worn devices. Those devices create resulting visual information by superimposing virtual items over the images of actual environment as it is captured by a camera installed on those devices; this is so called a *video see-through AR* (also called *video pass-through AR*). Unlike HMDs and HHDs, SDs the surrounding environment or specially dedicated surfaces to introduce visual information that corresponds to the virtual objects. Because the spatial display is not held or worn by the user, it offers different benefits over other AR visual displays. Figures 2–4 highlight the three AR display options: head-mounted, hand-held, and spatial visual display.



Figure 2. Head-mounted device. Source: Turner and Cruz (2022).

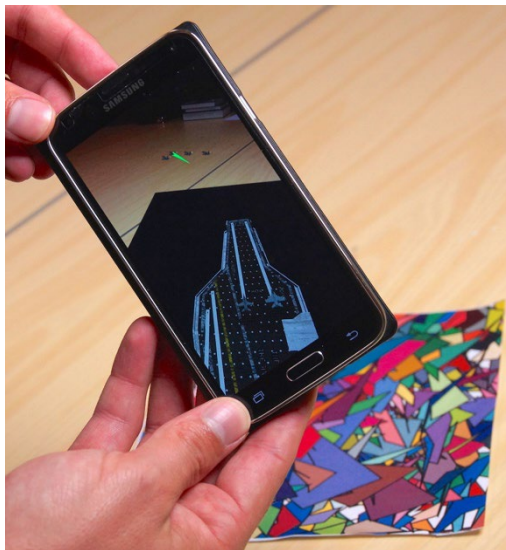


Figure 3. Hand-held augmented reality display. Source: Greunke (2015).



Figure 4. Virtual sand table, behavior analysis and synthesis for intelligent training project. Source: Sadagic et al. (2013).

2. Virtual Reality

Several definitions describe what the term VR means depending on when it was defined and in what domain the term is used. VR has many interpretations, and the working definition of VR used throughout this document is described by Brooks. Where he describes “a virtual reality experience as any in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint” (Brooks, 1999, p.16).

Over the past decade, advancements in VR technology and VR-supported devices have increased in personnel and professional use. As a result, it has become commonplace to use VR technology to conduct training when conditions are not always optimal or can save the company time, money, and other resources. Some examples of VR used to augment training in the real world include the military, medical domain (e.g., surgical procedures), and aviation (flight simulators). Figure 5, for example, highlights the use of VR technology to train medical personnel without an actual patient present. It was found that training conducted using VR HMDs increased performance and saved time and resources compared to performing medical training with actual patients.



Figure 5. VR and the transformation of medical education. Source: Pottle (2019).

The key difference between VR and AR is the amount of virtual (simulated) information presented to the user. Within VR, the entire environment is virtual, i.e., simulated and artificial. In AR, the device augments the actual environment by superimposing virtual objects within the sensory field; therefore, it is a combination of the information that originates from the real environment and information that represents the simulated environment.

3. Reality-Virtuality Continuum

Milgram and Kishino's reality-virtuality continuum is a crucial concept to grasp when seeking to understand the differences between VR and AR and the entire spectrum of media that spans between the real and virtual environments. Milgram and Kishino's reality-virtuality continuum, shown in Figure 6, categorizes mixed reality experiences to include AR and VR (Milgram et al., 1994). Within Milgram and Kishino's virtual continuum, the real environment is represented on the left side of the spectrum, and moving right on the virtual continuum is the mix of virtual and real environments. The right-most end of the continuum represents an environment that has only virtual objects. As discussed

by Milgram & Kishino, a mixed reality (MR) environment is the range between the real and virtual worlds but never only real or only virtual (Milgram et al., 1994).

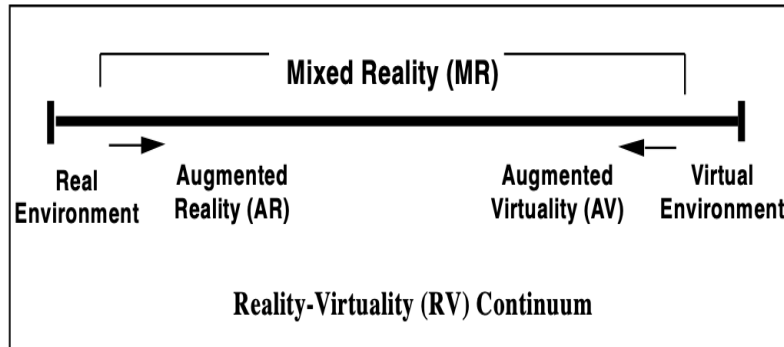


Figure 6. VR continuum. Source: Milgram and Kishino (1994).

4. Low-Cost Commercial-Off-the-Shelf Solutions

With the rapid development of VR and AR solutions, businesses rely on information technology that enables team collaboration and 3D information presentation and manipulation. The increase in user demand and desire for increased effectiveness and efficiency in conducting a variety of tasks has resulted in the emergence of low-cost COTS solutions found in both hardware and software domains. They exist on the commercial market and are readily available for sale to the public. The increased demand for low-cost COTS has permeated the industry to the point that it has become a prerogative of any business to use low-cost COTS to maintain a competitive advantage. Technological advances allow for increased processing power and storage capabilities while keeping the prices down. Additionally, the availability of cloud computing solutions allows many small and medium-sized companies to afford and incorporate low-cost COTS technologies within the workforce (Agrawal et al., 2016).

As discussed in Chapter II.B, Virtual Reality and Augmented Reality, using low-cost COTS for HMD in both VR and AR would be highly beneficial for Army staff members conducting MDMP to analyze, collaborate, and recommend a COA for a commander. To use HMD efficiently for MDMP, one could use both VR and AR solutions.

Both technologies support the essential capabilities needed for human interaction, such as hand tracking and the ability to engage multiple users and collaborate.

The sections that follow introduce several examples of low-cost VR and AR COTS display solutions.

a. Meta Quest 2

The Meta Quest 2 HMD, formerly Oculus Quest 2, is one VR low-cost COTS option that can provide some capabilities necessary for small team collaboration. One of the main benefits of Meta Quest 2 is that it is a stand-alone system and does not require hardwired connections to a personal computer. That HMD enables relatively easy set-up and use and allows the users to navigate the VR world in six degrees of freedom (DOF) (Figure 7).

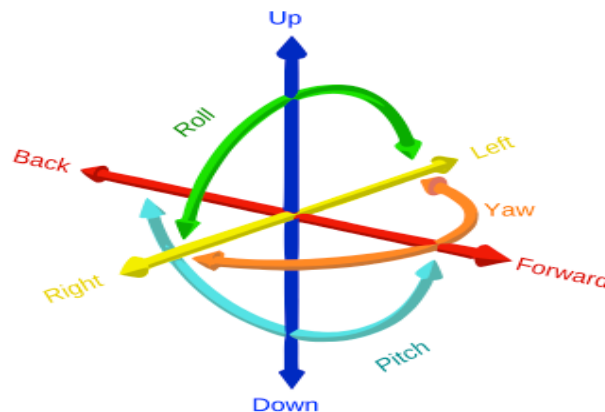


Figure 7. Six degrees of freedom. Source: GregorDS (2015).

The Meta Quest 2 (Figure 8) is an HMD with two controllers that enable users to move around, engage with other users, manipulate, and interact with the objects in a VE. Controllers have buttons for selection, and multiple sensors that, together with the cameras integrated in HMD, enable hand tracking in a VE. The accuracy of tracking solutions has also improved. For example, the research conducted by Carnevale that was focused on the accuracy of Oculus Quest 2 for shoulder rehabilitation (device was evaluated for detecting human movement), the hand and head tracking of the Oculus Quest 2 HMD were found to

be more than enough for medical research. (Carnevale et al., 2022) According to a review by CNET and Stein they found that while tracking movement has satisfactory precision, the system's processing capability is constrained, which results in occasionally acceptable images for the user, but can also lead to latency in image rendering (CNET & Stein, 2019).

Meta Quest 2 has a field of view (FOV) of 90 degrees, slightly larger than the original Quest's FOV. In terms of weight, the Meta Quest 2 weighs 503 grams, which is lighter than the original Oculus Quest. The lighter weight makes Meta Quest 2 more comfortable for extended periods. The battery life of Meta Quest 2 is around 2–3 hours of continuous use. However, this can vary depending on factors such as the types of apps being used and the screen brightness. The Meta Quest 2 features an 1832 x 1920 resolution per eye, with a refresh rate of up to 90Hz. It also has a built-in microphone for audio input, speakers and a 3.5mm headphone jack for audio output. In addition, the headset comes with two Touch controllers for intuitive hand-tracking (Jones, 2023).

The Meta Quest 2 (Figure 8), being a VR visual display solution, does not allow an unobstructed view of the real world—instead, other users need to be represented with their avatars. Additionally, full fidelity of the user's body, facial and hand gestures, are hard to model and animate in VR, and the ability to track the user's eye gaze is also not available in this type of HMD. The same elements are paramount for conducting a productive collaborative session with a small team. Additionally, the HL2 has a flip-up display allowing users to either interact in their AR environment or engage in the real world (Figure 8). These critical HL2 features allow the user to see and interact with other staff members for an extended period making this an ideal AR solution for MDMP.



Figure 8. Meta Quest 2.

b. HoloLens 2

In contrast to the Meta Quest, the HoloLens 2 (HL2) (Figure 9) is an AR HMD solution that does not have controllers and allows the user to see the elements of real environments. That, in turn, allows users to collaborate with others and see their body, facial and hand gestures in real time. The user interaction for HL2 is supported by hand and gaze tracking—a user can gaze, touch, point (‘hand ray’), air tap, and “pinch” within the AR environment. That allows users to select, confirm, manipulate, and move objects within the virtual environment.



Figure 9. HoloLens 2.

HL2 employs four visible light cameras; their function is to track the movement of the head, the hands, and the real environment for precise tracking. Additionally, the HL2 employs the built-in color video camera to capture a composite visual representation of the actual conditions (real environment) and the virtual objects superimposed onto it, which can then be saved as an mp4 file. The HL2 is also equipped with two IR cameras that offer additional data for eye tracking.

When considering using HL2 for MDMP, we recognize that the HL2 offers additional benefits over other AR HMD solutions: it is an enhanced field of view of 52 degrees, a weight of 566 g, and a battery life of 3 hours. (Palumbo, 2022) Additionally, as Figure 10 shows, the display unit can be flipped up without powering off or removing the device. That feature is a tremendous advantage for its usage during long sessions in MDMP and a significant advance over other AR HMD solutions. Additionally, the HL2 has a flip-up display allowing users to either interact in their AR environment or engage in the real world (Figure 10). These critical HL2 features allow the user to see and interact with other staff members for an extended period making this an ideal AR solution for MDMP.



Figure 10. HoloLens 2 flipped-up.

C. EFFECTIVENESS OF AR FOR SMALL TEAM COLLABORATION IN MILITARY OPERATIONS

The U.S. Army has been exploring AR technology to improve small-team collaboration and increase situational awareness. AR provides soldiers with real-time information and visual aids that can be superimposed over the physical environment. That can enhance communication and collaboration between the team members—it provides a shared understanding of the environment, task, and objectives. In a report produced by the Naval Research Laboratory that compared VR and AR, the authors stated that “AR allows for more realistic interaction among multiple trainees since they see each other through their natural vision as opposed to an avatar representing a particular person” (Livingston et al., 2011, p.4).

A very similar effort was conducted by the U.S. Army and the North Atlantic Treaty Organization (NATO). Those organizations have been testing smart glasses and AR heads-up displays (HUDs), such as the Microsoft HoloLens, to display maps, navigation aids, and real-time intelligence updates (Slyusar, 2021). Those displays allowed soldiers to see crucial information in real-time without looking away from their surroundings; the system improved their ability to make quick, informed decisions. Figure 11 depicts NATO’s use of AR for military collaboration among staff members while supporting military operations.



Figure 11. Augmented reality utilization in military operations. Source: Slyusar (2021).

However, AR effectiveness can be limited if soldiers are not trained, not prepared to use AR technology, or the interface is crowded with information and virtual objects placed within the AR space that cause cognitive overload for the users (Livingston et al., 2011). To derive the best value from the system (or any system, for that matter), soldiers must be familiar with the AR system, and know how to use it to access information and interpret the information displayed for effective communication. To use it effectively in real-world military operations, they also must be able to integrate AR into their existing processes and procedures.

Sadagic et al. explored the advantages and practical applications of using MR technology for mission planning as a part of the Behavioral Analysis and Synthesis for Intelligent Training (BASE-IT) project (Sadagic et al., 2013). The authors proposed a process of capturing live training data associated with each trainee by means of 3D real-time data capture (3D data acquisition), analyzing individual and team performance, and generating comprehensive After-Action Review (AAR) reports; the ultimate goal was to enhance behavioral observation and improving the quality of AAR in a highly occluded training environment (rural and urban environments). Researchers also designed a round-

shaped mixed-reality virtual sand table to assist small team collaboration on mission planning task (Figure 4). That system used physical artifacts—wooden blocks painted in white—and projective display technology to simulate the look and feel of a traditional sand table. Three projectors presented ‘all round’ imagery onto wooden blocks and surfaces, and the tracked digital pen allowed users to add graphical annotations and draw onto the projected environment. People around the table were able to see each other, freely observe the textured objects on the table (no special glasses were needed) and use digital pen to add symbols and plan the routes of approach.

Additionally, previous research conducted by Knobloch proposed an AR-based system for military mission planning that combines different types of data, such as maps, terrain information, and 3D models, to create a virtual sand table (Knobloch, 2020). The system aimed to enhance situational awareness, reduce planning time, and improve communication and collaboration among team members. He successfully created a portable rendition of the virtual sand table utilizing COTS items through his investigation. This development served as a proof-of-concept, showcasing the potential of AR technology by surpassing the conventional capabilities of the traditional sand table. The method employed by the researcher involved the seamless integration of an accurately scaled 3D model representing the actual terrain, coupled with an innovative first-person perspective that enabled users to examine the details closely (Knobloch, 2020). Knobloch demonstrated the possibility of using COTS to create a virtual sand table allowing users to view and analyze terrain in real time. The system allowed both the third-person view and exploration of the terrain from the first-person perspective (teleportation to terrain).

One of the promising AR technologies the Army is looking to make a Program of Record is the Integrated Visual Augmentation System (IVAS). The IVAS is a cutting-edge military technology developed by Microsoft in collaboration with the U.S. Army using HoloLens technology (Inspector General, 2022). IVAS is a specialized system that combines various capabilities, such as AR, thermal imaging, and positional tracking, to enhance a soldier’s situational awareness and combat effectiveness. The IVAS provides soldiers with a highly immersive and interactive AR experience, overlaying digital information onto their physical environment in real time (Inspector General, 2022). It has

been designed to enhance soldiers' training and performance by providing them with real-time data, maps, and other visual cues, allowing them to navigate and operate more effectively in complex environments. The Department of Defense Inspector General report notes that the IVAS system has shown promise in enhancing soldiers' situational awareness and combat effectiveness. However, the report also identifies several challenges and risks associated with the implementation of the system, including cybersecurity vulnerabilities, logistical concerns, and the need for comprehensive training and support for soldiers using the system (Inspector General, 2022).

The collective experiences derived from multiple studies and research projects reviewed in this section suggest that the quality and reliability of AR technology are also critical in determining its effectiveness. The AR systems must be robust and reliable so that soldiers can trust the information presented on the visual display, especially if they use the device in demanding and challenging environments. The technology must also be designed to meet the specific needs of military small-team collaboration to support MDMP effectively. The effectiveness of AR for small-team collaboration will depend on the availability and quality of AR technology, the training and preparation of soldiers, and the integration of AR into existing processes and procedures. However, with the right technology, training, and preparation, AR can significantly enhance small-team collaboration and situational awareness when planning military operations.

D. AUGMENTED REALITY SANDTABLE (ARES)

1. Intent and Design

Amburn et al. introduce the Augmented Reality Sandtable (ARES) as a low-cost COTS that provides a geospatial terrain visualization system; the tool uses COTS products to create a tangible user interface for simulation and training (Amburn et al., 2015). The technique combines projection technology with a Microsoft Kinect sensor and a laptop—the setup is intended to enhance the capabilities of traditional military sand tables through the use of AR. Previous related work has focused on virtual and augmented reality systems for military training and simulation, but those systems are often expensive and require specialized hardware. ARES is unique in its use of affordable COTS components and its

focus on providing a tangible user interface allowing numerous staff sections to analyze and manipulate the terrain in real-time (Amburn et al., 2015). Figure 12 shows the basic setup and technologies integrated in ARES display the terrain in AR.

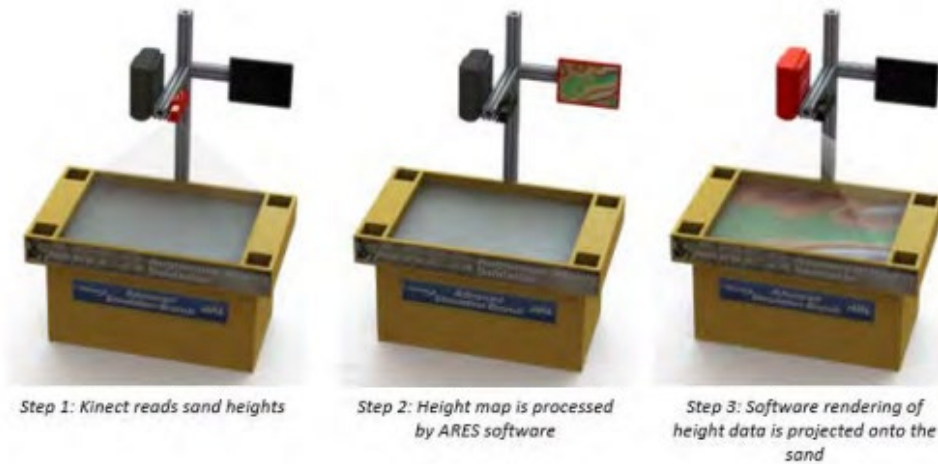


Figure 12. Augmented reality sand table: Terrain recognition process.
Source: Amburn et al. (2015).

2. How ARES Works

The ARES system uses a projective display solution to produce visual information. The geospatial data are projected onto a sand surface located on top of the table (just like any traditional sand table), and that visual information is augmented with additional virtual data (Figure 13). The Microsoft Kinect sensor and laptop are used to acquire 3D information about the surface of the sand mass on the table, and that information is further used to calculate and project correct contour information and any other symbol (visual object) that may be needed (Amburn et al., 2015). The Kinect sensor also detects the user's hand movements and gestures above the sand table surface, which allows user interaction with the virtual information. The system is designed to be modular, allowing for integrating different hardware components such as controllers and tablets to support the placement of military symbology and support various simulation and training scenarios. The software used by ARES is based on an open-source platform that allows developers to create and integrate custom applications (Amburn et al., 2015).

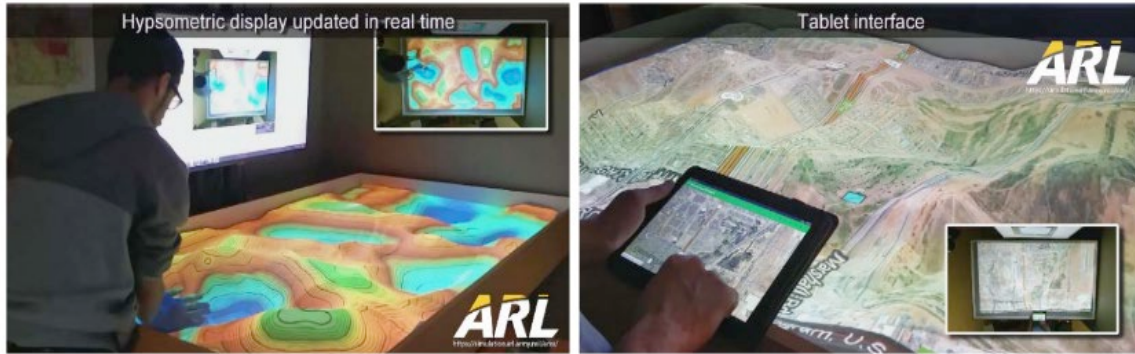


Figure 13. ARL's ARES. Source: DignitasTechnologies (2015).

3. ARES Advantages and Disadvantages

The ARES system offers several advantages over traditional military training solutions, simulations, and other virtual and augmented reality systems. The system is cost-effective due to its use of low-cost COTS components. Its service-oriented architecture makes it a valuable resource for military personnel to collaborate in various planning exercises. ARES also provides a tangible user interface that allows users to interact with physical and digital information more intuitively and naturally compared to other systems displaying terrain in AR (Amburn et al., 2015). Additionally, the system is customizable and can be modified to meet specific training and simulation needs.

However, ARES also has some limitations to consider. The resolution of the projected image onto the sand table surface may be limited compared to other systems; that may impact the quality of the user experience. The sand table surface may provide fewer interaction capabilities than other systems incorporating virtual objects, handheld controllers, or input devices such as HL2. Additionally, the system requires a laptop and a projector, which may make it less portable than other systems HMDs. Finally, sand is not a perfect visual display surface—the sand table surface and projection may not provide the best quality imagery like other virtual and augmented reality systems that use high-fidelity graphics. Despite its limitations, ARES offers a unique and cost-effective approach to geospatial terrain visualization, simulation, and training with potential applications in other domains.

4. Analysis of ARES Performance

A study by M. Boyce et al., published in *Military Psychology* in 2019, compared task performance on a flat surface using a tablet versus ARES (Boyce et al., 2022). The research discovered that augmenting the level of detail in the terrain’s depiction did not significantly enhance comprehension of the terrain within a simulated planning setting using ARES. Nonetheless, employing a surface shaped according to the topography resulted in an improved perception of usability for the interface and a reduction in cognitive burden compared to a flat surface. However, despite these benefits, the utilization of ARES did not have a notable effect on task performance concerning accuracy and response time (Boyce et al., 2022). The research suggests that incorporating topographical features in an interface can enhance usability and reduce cognitive load, but adding more terrain details may not necessarily lead to improved task performance (Boyce et al., 2022).

E. CHAPTER SUMMARY

This chapter introduces fundamental concepts and a literature review focused on the research domain discussed in this thesis. The topics discussed in the chapter included AR and VR technologies and the concept of the Reality-Virtuality continuum as proposed in (Milgram & Kishino, 1994). Additionally, this chapter discussed different low-cost off-the-shelf VR and AR solutions and reviewed their advantages and disadvantages. Lastly, this chapter discussed the use of AR technology for small-team collaboration and provided more details on one solution—the ARES system.

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III. TASK ANALYSIS: CURRENT MDMP PRACTICES

A. INTRODUCTION

This chapter overviews how the U.S. Army military staff personnel currently conduct MDMP. The text focuses on the inputs and outputs each WFF provides during MDMP that produces an OPORD. Additional material discussed here includes the planning tools and collaboration techniques used for recommending a COA to a commander and the inherent limitations of current practices.

B. ARMY DESIGN METHODOLOGY FOR PLANNING (ADM)

According to ADP 5–0, the Army Design Methodology (ADM) is a methodology the U.S. Army staff planners use to apply critical and creative thinking to understand, visualize, and analyze different problem-solving approaches (Headquarters, Department of the Army, 2019). The ADM is used for conceptual planning and integrated into the MDMP to create detailed and executable plans.

The ADM methodology consists of three main steps: (1) *establishing an operational context*, (2) *defining the problem*, and (3) *devising an operational strategy to address the problem* (Headquarters, Department of the Army, 2019). The result of conducting ADM is an improved understanding of the mission and objectives, and the approach staff members utilize to address and solve those objectives. Figure 14 depicts ‘framing the operational environment’ and is composed of five different states: (1) current state, (2) desired end state, (3) frame the problem, (4) develop an operational approach, and (5) develop the plan. (MDMP Lessons and Best Practices Handbook, 2015) The MDMP starts with developing the plan and is the transition point from conducting conceptual planning into detailed planning (U.S. Army Combined Arms Center, 2015).

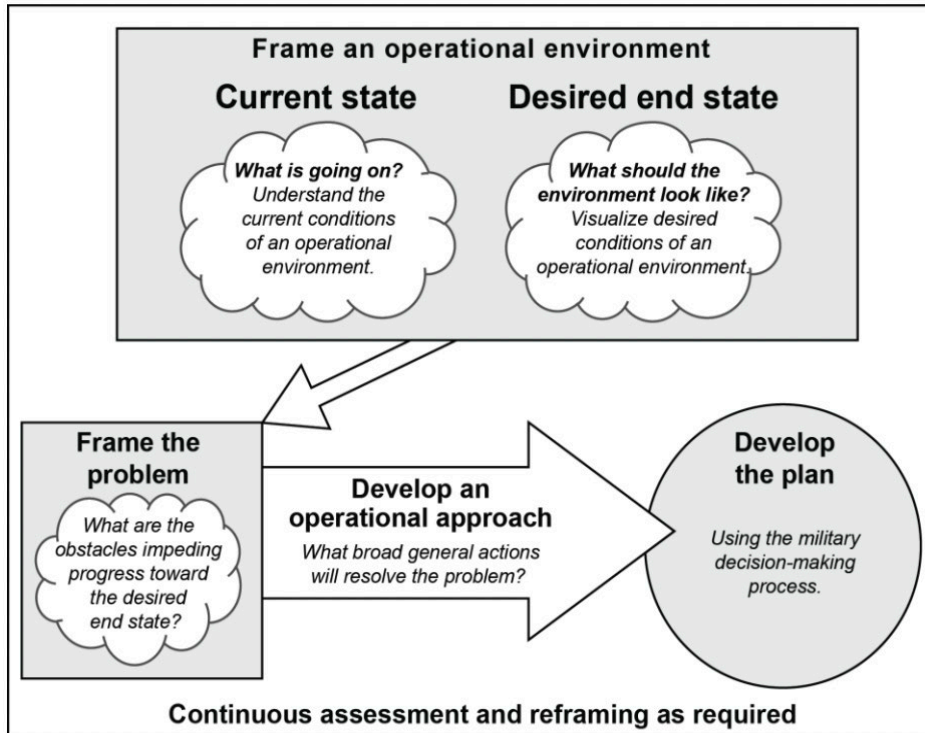


Figure 14. Frame the operational environment. Source: Headquarters, Department of the Army (2019).

C. MILITARY DECISION-MAKING PROCESS

The MDMP is a planning process that incorporates the actions of the command, staff, subordinate units, and joint or coalition partners, to facilitate coordinated planning (U.S. Army Combined Arms Center, 2015). The goal of the MDMP is to understand the problem and develop and compare the COA. The commander selects COA that achieves the desired end state and produces an OPORD for unit execution.

The MDMP requires continuous collaborative, parallel planning from higher headquarters and subordinate units. Information is continuously passed from higher headquarters staff through subordinate and supported units for bottom-up plan refinement. According to ADP 5–0, It is recommended that commanders and staff members engage in active collaboration within their organization to establish a shared comprehension of the mission, contribute to the development of COAs, participate in decision-making, and address any potential conflicts among the various organizations

before presenting a COA to the commander (Headquarters, Department of the Army, 2019). The MDMP is composed of a series of steps that the U.S. Army staff personnel conduct before the publication of the OPORD, as shown in Figure 15 (U.S. Army Combined Arms Center, 2015).

Key inputs	Steps	Key outputs
<ul style="list-style-type: none"> Higher headquarters' plan or order or a new mission anticipated by the commander 	<p>Step 1: Receipt of Mission</p>	<ul style="list-style-type: none"> Commander's initial guidance Initial allocation of time
Warning order		
<ul style="list-style-type: none"> Commander's initial guidance Higher headquarters' plan or order Higher headquarters' knowledge and intelligence products Knowledge products from other organizations Army design methodology products 	<p>Step 2: Mission Analysis</p>	<ul style="list-style-type: none"> Problem statement Mission statement Initial commander's intent Initial planning guidance Initial CCIRs and EEFls Updated IPB and running estimates Assumptions Evaluation criteria for COAs
Warning order		
<ul style="list-style-type: none"> Mission statement Initial commander's intent, planning guidance, CCIRs, and EEFls Updated IPB and running estimates Assumptions Evaluation criteria for COAs 	<p>Step 3: Course of Action (COA) Development</p>	<ul style="list-style-type: none"> COA statements and sketches - Tentative task organization - Broad concept of operations Revised planning guidance Updated assumptions
<ul style="list-style-type: none"> Updated running estimates Revised planning guidance COA statements and sketches Updated assumptions 	<p>Step 4: COA Analysis (War Game)</p>	<ul style="list-style-type: none"> Refined COAs Potential decision points War-game results Initial assessment measures Updated assumptions
<ul style="list-style-type: none"> Updated running estimates Refined COAs Evaluation criteria War-game results Updated assumptions 	<p>Step 5: COA Comparison</p>	<ul style="list-style-type: none"> Evaluated COAs Recommended COAs Updated running estimates Updated assumptions
<ul style="list-style-type: none"> Updated running estimates Evaluated COAs Recommended COA Updated assumptions 	<p>Step 6: COA Approval</p>	<ul style="list-style-type: none"> Commander approved COA and any modifications Refined commander's intent, CCIRs, and EEFls Updated assumptions
Warning order		
<ul style="list-style-type: none"> Commander approved COA and any modifications Refined commander's intent, CCIRs, and EEFls Updated assumptions 	<p>Step 7: Orders Production, Dissemination, and Transition</p>	<ul style="list-style-type: none"> Approved operations plan or order Subordinates understand the plan or order

Figure 15. Military decision-making process. Source: Headquarters, Department of the Army (2014).

D. TASK OBJECTIVE, STAFF, STEPS, AND TOOLS

MDMP is a collaborative effort among various military staff members. During this process, the staff develops and evaluates options to achieve mission objectives. According to the Center of Army Lessons Learned handbook, the following is the list of steps for conducting MDMP:

- Receipt of mission.
- Mission analysis.
- Course of action development.
- Course of action analysis.
- Course of action comparison.
- Course of action approval.
- OPORD production. (U.S. Army Combined Arms Center, 2015)

The first step in MDMP is the *Receipt of Mission* initiated upon receipt of an OPORD from a Higher Headquarters unit or in anticipation of a mission. During this phase, a commander provides the staff with their initial guidance, and the Executive Officer or Chief of Staff gives a tentative timeline to determine the time for planning; during the same period, the staff is expected to gather their planning tools. The primary tool used during this step of MDMP is the development of the running estimates on capabilities within their respective WWF by the staff sections and evaluation of the specified and implied tasks defined in the higher headquarters OPORD. Finally, the receipt of the mission phase is complete with the publication of a warning order (WARNO) notifying staff sections and units affected by the pending mission.

In the *Mission Analysis* (MA) step, the team persists in scrutinizing the order from the higher headquarters, aiming to achieve a shared comprehension of the mission, intent, available resources, restrictions, boundaries, and explicit and implicit duties (MDMP Lessons and Best Practices Handbook, 2015). One of the primary activities is the Intelligence Preparation of the Battlefield (IPB), further discussed in Chapter III.C, Intelligence Preparation of the Battlefield. At the end of that step, the staff develops the

proposed problem and mission statement, conducts a mission analysis brief for the commander, and issues WARNOs for all units affected by the mission.

During the *Course of Action Development step*, the staff collaborates to generate potential solutions to the problem. This step involves brainstorming and evaluating different approaches, considering the advantages and disadvantages of each course of action sketch. The staff has to ensure that all courses of action are evaluated and that the best options are identified for further analysis. During this phase, each WWF synchronizes with other staff sections to ensure the potential course of action is supportable by each WWF. According to the U.S. Army's MDMP article, each prospective COA is examined for validity using the following screening criteria. According to the Center of Army Lessons Learned handbook, the following criteria must be met for different COAs:

1. Feasible: The COA can accomplish the mission within the established time, space, and resource limitations.
2. Acceptable: The COA must balance cost and risk with the advantage gained.
3. Suitable: The COA can accomplish the mission within the commander's intent and planning guidance.
4. Distinguishable: Each COA must differ significantly from the others, such as the scheme of maneuver, lines of effort, phasing, use of reserve forces, and task organization. (U.S. Army Combined Arms Center, 2015, p. 27)

In the *COA Analysis* phase, also known as the *wargaming phase*, the staff evaluates each course of action against the established mission objectives. First, the team considers each option's feasibility, risks, and costs to identify potential execution problems and decides on the conduct of the wargame. The most common conduct of wargame is using the "action, reaction, and counteraction methods of friendly and enemy forces within the AO" (U.S. Army Combined Arms Center, 2015). Subsequently, the WWFs collaborate to pinpoint conceivable obstacles and prospects linked with every alternative and assess the probability of achieving success. The COA Analysis involves a systematic approach that follows specific guidelines and procedures. They examine every aspect of the operation, including the strengths and weaknesses of the forces and

the enemy’s disposition, to develop a clear picture of the AO (U.S. Army Combined Arms Center, 2015). After the COA Analysis concludes, refinements are made to each COA, and a synchronization matrix and support template are created to evaluate each COA against one another.

The *COA Comparison* phase involves a systematic approach to assess COAs in an unbiased manner, using pre-determined evaluation criteria that both the commander and staff accept (U.S. Army Combined Arms Center, 2015). Assessing the strengths and limitations of COAs enables the selection and further development of the COA with the best chance of success in an operation plan or operation order. The most common method for evaluating each COA against the other uses a decision matrix, as shown in Figure 16. At the end of this phase, the staff presents a commander with a decision brief where they choose the COA that is most likely to succeed (U.S. Army Combined Arms Center, 2015).

Decision-support matrix				Supporting NAI / CCIR / Unit
DP #	Decision	Criteria / Conditions	Action	
	What decision must be made?	Criteria is condition(s) that when met require decision to be made	Actions to be executed	
1	Execute chemical artillery strike against 21 st Infantry Division artillery?	If 21 st Infantry Division artillery have been located within 21.9 kilometer range of our 251s	Then request chemical-strike authority and release of chemical munitions from 18 th DTG	NAI: 1, 10 CCIR: 5 Unit: 1812 Infantry Battalion
2	Use ADA to shoot down 21 st Infantry Division aircraft (fixed or rotary)?	1. If SEAD attacks were observed and after initial U.S. company has landed 2. If ADA in local area have been targeted, then local commander is encouraged to use remaining assets	1. Then shoot down lift assets after Soldiers have disembarked or as they lift off 2. Then shoot down threat	NAI: 20, 21 CCIR: 1, 2, 5 Unit: 3039 Cav Squadron, 1814 Armor Battalion
3	Commit our reserve Armor battalion to southern AoA?	If U.S. forces gain a foothold at BP 4	Then deploy Armor battalion	NAI: 7 CCIR: 3, 4 Unit: 3067 AT Battalion

Figure 16. Decision-support matrix. Source: Klein and Hasting (2016).

Following a briefing on potential COAs, the commander selects the most effective option for achieving the mission’s objectives—this is *COA Approval* phase.

If none of the COAs are deemed suitable, the staff initiates a fresh round of MDMP from the COA development phase. Whenever the commander modifies an existing COA or proposes a new one, the staff conducts a wargame to evaluate the revised plan and recommends it to the commander based on the results. Once the commander has given final guidance, the WFF's issues a warning order (WARNORD) to subordinate units, outlining the necessary actions as outlined in the Center of Army Lessons Learned handbook for conducting MDMP. The elements of the WARNORD are:

- The AO.
- The unit's mission.
- The commander's intent.
- The concept of operation.
- Tasks assigned to subordinate units.
- A timeline to include rehearsals. (U.S. Army Combined Arms Center, 2015)

E. INFORMATION PREPARATION OF THE BATTLEFIELD

The Information Preparation of the Battlefield (IPB) is a joint venture with participation from all staff sections; it is driven by the intelligence team and was first released during the Mission Analysis phase of MDMP. During the Mission Analysis process, the intelligence products provided to the commanders and staff members ensure a shared understanding of the crucial aspects of the operational area and the relevant areas of interest that could affect the mission's outcome (Headquarters, Department of the Army, 2019). IPB comprises four steps, with specific intelligence products developed during each step, as shown in Figure 17.

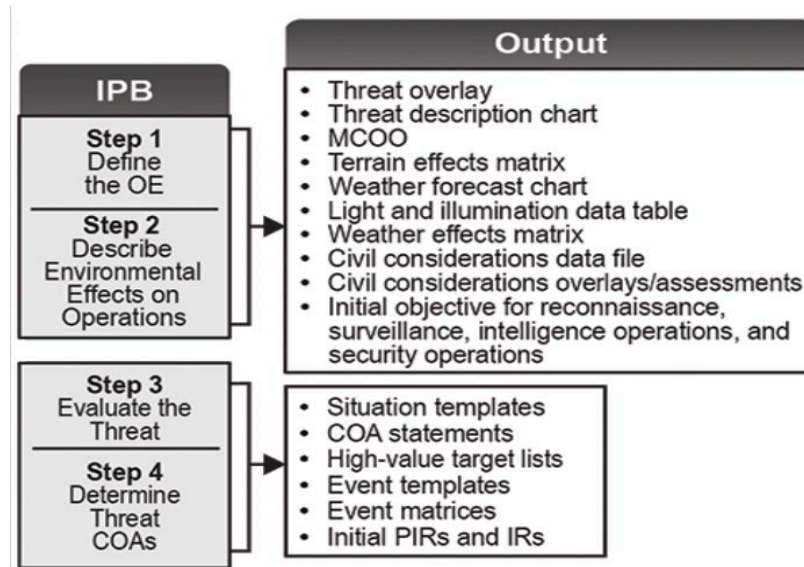


Figure 17. IPB product outputs. Source: Lobdell (2019).

Defining the operational environment involves identifying the physical, human, and other factors influencing military operations. It includes analyzing terrain, weather, and other natural factors. Furthermore, it is imperative to identify and establish the political, economic, social, and cultural conditions in the operational area, areas of interest, and areas of influence (Lobdell, 2019). The next step in the IPB process is to *Describe the environmental effects on operations*. This step involves analyzing how the operational environment will affect friendly and enemy forces. It includes assessing the impact of terrain, weather, and other environmental factors on mobility, communications, and other critical aspects of military operations. *Evaluating the threat* involves identifying and analyzing enemy forces and their capabilities. It includes assessing their strengths, weaknesses, potential courses of action, likely intentions, and objectives. This phase aims to comprehend the potential impact of a threat on friendly operations (Lobdell, 2019). The last step in the IPB process is *Determine enemy courses of action* which involve developing a range of potential enemy courses of action based on the analysis of the threat. It includes identifying enemy objectives and developing a plan to counter their actions (Lobdell, 2019).

F. CURRENT USE AND LIMITATIONS OF 2D MAPS AND INTELLIGENCE PRODUCTS

As discussed in Chapter III.C, Intelligence Preparation of the Battlefield, the intelligence WFF is the primary staff section responsible for displaying the AO, mobility corridors, key terrain, and enemy disposition and COAs. The intelligence section accomplishes the battlefield visualization using multiple overlays on an analog 2D map, as seen in Figure 18. While the U.S. Army staff possesses tools for displaying terrain in 3D, almost all planning is conducted on 2D maps and overlays, which has inherent limitations.

interpretation. Overall, the researchers concluded that integrating 2D and 3D improved performance and problem-solving among test candidates (Dübel et al., 2014). Figure 19 shows how combining 2D and 3D achieved the highest results for performance and problem-solving.

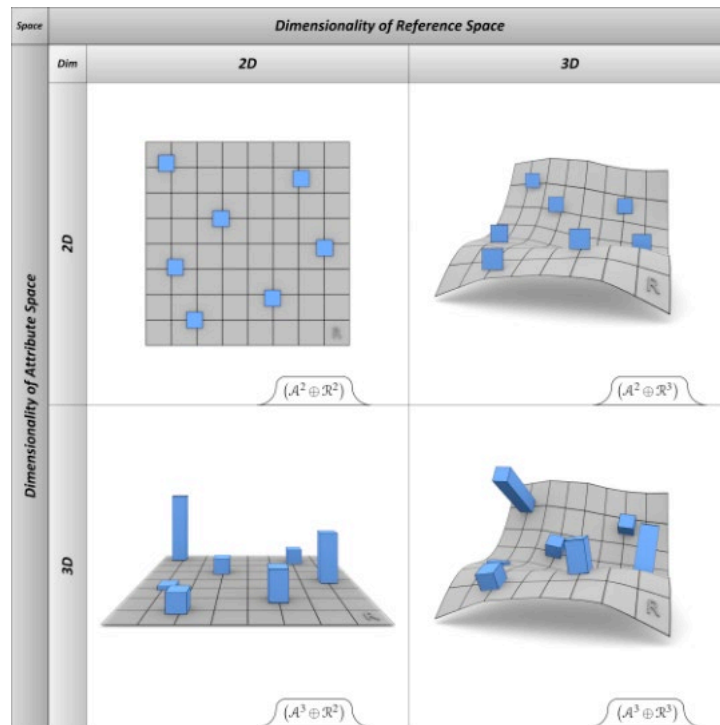


Figure 19. Optimizing 2D and 3D visualization. Source Dübel et al. (2014).

An additional research study was conducted by Carbonell Carrera et al. in 2017. They organized a workshop to teach maps using 2D maps alone or a combination of 2D maps and digital 3D and physical representations. The study observed notable variations in the experimental groups' pre- and post-workshop knowledge scores. Additionally, the study established a considerable difference in performance between the 2D maps-only group and the group taught using a combination of 3D digital and physical representations. Notably, the group trained with 3D effects performed better when determining the steepest slope or locating terrain features (Carbonell Carrera et al., 2017).

2D maps are commonly used to represent geographic data but have several limitations compared to 3D maps. One of the main drawbacks of 2D maps is a lack of cues supporting depth perception, making it challenging to accurately represent changes in elevation and terrain features. Additionally, 2D maps provide a limited perspective of their geographic area, making it difficult to visualize the relationship between different components and how they fit together. The incomplete information provided by 2D maps about the real-world environment is another significant limitation. In addition, 2D maps cannot capture the complexity of 3D features, such as buildings, bridges, and other structures. Furthermore, it is difficult for 2D maps to accurately represent overlapping features, making it challenging to understand the relative positions of different features. Finally, 2D maps often need to be more accurate in representing data because of the distortions that occur when depicting a 3D object in 2D. In contrast, 3D maps provide a more accurate representation of geographic data, enabling better visualization and analysis, including the use of immersive tools. However, 3D maps can also be more complex and resource-intensive to create and use (Dübel et al., 2014).

G. STAFF COLLABORATION DURING MDMP

During MDMP, the U.S. Army’s WWFs use various tools to collaborate and analyze information for a common understanding. The tools staff sections use for MDMP range from the whiteboards for brainstorming and analysis to sophisticated mission command systems for displaying a COP and communication equipment such as SharePoint to consolidate and distribute information. The methods and tools WWF use during MDMP start with rudimentary tools, and as MDMP progresses, the complexity and the number of tools increase with each step of the planning.

According to ADP 5–0, planning during MDMP is the “art and science of understanding a situation, envisioning a desired future state, and the effective ways of bringing that future about” (Headquarters, Department of the Army, 2019). During MA staff sections’ predominant tools are analog products such as whiteboards, maps with overlays, some form of Microsoft suite to develop decision-support and briefing products, and a secure communication system to collaborate and distribute information. In the early phases

of MDMP, the predominant communication method is face-to-face or using some form of secure communication equipment when staff members are geographically dispersed. Figure 20 highlights different tools staff members operate in the early phases of MDMP to understand and visualize a mission.



Figure 20. MDMP planning.
Source: U.S. Army Combined Arms Center (2016).

As MDMP progresses from COA Development through order production, each WFF possesses mission command systems that help the staff analyze data, visualize, and help make informed decisions. The most common mission command tool all WFFs use for planning during MDMP is the Command Post of the Future (CPOF). This mission command tool enables the warfighter to visualize the battlefield and have command and control of a battlefield through collaboration between each WFF (General Dynamics, n.d.-a).

Additionally, the Fires WFF uses the Advanced Field Artillery Tactical Data System (AFATDS) mission command system to augment mission planning for coordination, placement of units, and execution of fires for mortars, field artillery cannons,

rockets and missiles, close air support, attack aviation, and Naval surface fire-support systems (Program Executive Office Command Control Communication-Tactical, n.d.).

The primary mission command system the Intelligence WWF uses for mission planning and execution is the Distributed Command Ground System-Army (DCGS-A). This mission command system used by the intelligence WWF assists commanders and staff in visualizing the battlefield by understanding the threat of other aspects relevant to the operational environment (Distributed Common Ground System-Army (DCGS-A), n.d.).

Lastly, the Tactical Airspace Integration System (TAIS) and Air and Missile Defense Planning and Control System (AMDWS) mission system are critical for airspace management. The TAIS is the Army's mission command system providing air-ground situational awareness of friendly and enemy air activity. (General Dynamics, n.d.-b) Meanwhile, the AMDWS provides air and missile defense operations at all levels (U.S. Army Acquisition Support Center, n.d.).

Collaborative software such as SharePoint and secure email are the primary methods for WWFs to share documents, track progress, and communicate with other team members. Knowledge Management of these systems is critical throughout MDMP for collaboration and information sharing between WWFs. McInerney describes the importance of Knowledge Management as being "critical for the transfer of tactic or implicit knowledge to explicit and acceptable formats to achieve the organization's mission" (McInerney, 2002).

Collaboration between staff members during MDMP is a complex and resource-intensive task requiring various mission command systems, digital and analog products to display information and support constant synchronization between staff members to ensure their shared understanding.

H. STAFF RECOMMENDATION TO A COMMANDER

As discussed in Chapter III.G, Staff Collaboration during MDMP, WWFs use various tools and methods to analyze information and recommend to a commander a COA which they believe will achieve the mission's objective. One of the most common ways

military staff brief a commander is through PowerPoint or a similar application from the Microsoft suite that operates with analog maps to present information. The commander relies on their experience, commander-to-commander dialogue with higher headquarters, and knowledge and experience to decide on recommended COAs or have the staff adjust the current plan.

PowerPoint application has become a prevalent tool among staff for consolidating and presenting mission information concisely, owing to the availability of several mission command systems and analytical tools. Figure 21 highlights the use of PowerPoint by the 1st Calvary Division to brief an enemy situation template for a rafting and bridging operation in support of a battalion Situational Tactical Exercise.

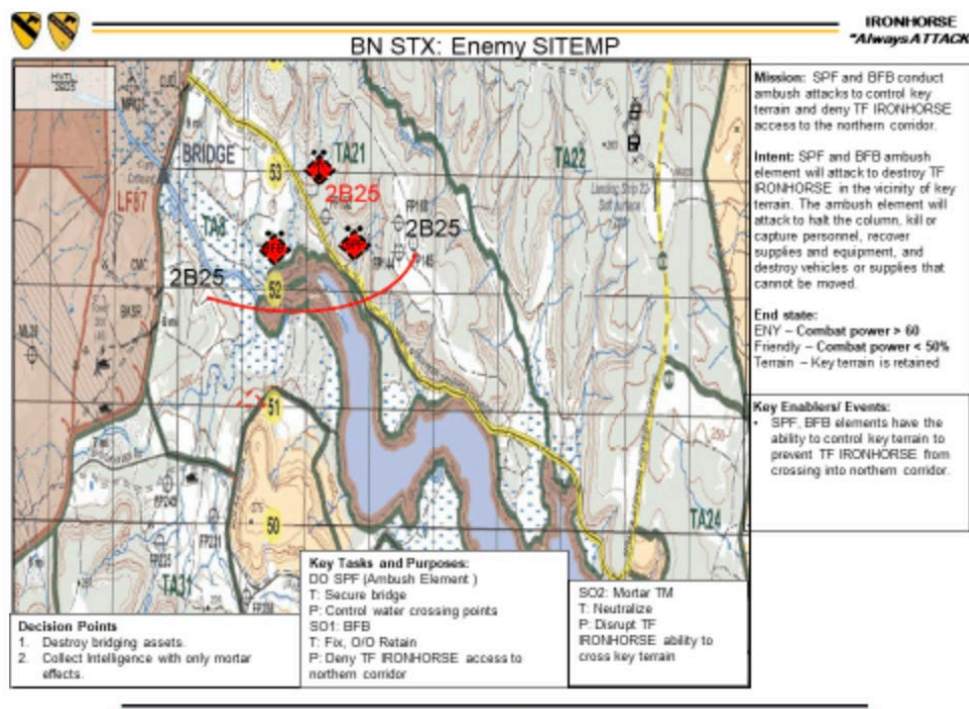


Figure 21. 1st Calvary Division situation template.
 Source: Schoenfeldt and Stalling (2021).

Consolidating and displaying information using an application such as PowerPoint or similar has several benefits and hindrances. For example, one of the primary benefits of

using PowerPoint to brief a commander is that the technology allows staff sections to take information from numerous mediums and consolidate it in an easy-to-read format, allowing a commander to make an informed decision on a recommended COA. However, the use of PowerPoint has been criticized as staff sections are consolidating vast amounts of information into easy-to-read bulletized comments and stifling critical thinking. For example, in a statement from General McMaster to Times magazine on the Army's use of PowerPoint, he stated, "the program stifles discussion, critical thinking, and thoughtful decision making" and went on further to express "it's dangerous because it can create the illusion of understanding and the illusion of control. Some problems in the world are not bullet-izable" (Gralla, 2010).

I. GAPS IN CURRENT PRACTICES OF MDMP

MDMP is an intensive process requiring a vast amount of time and resources for military planners to formulate an OPORD to support a mission. They use numerous mission command systems, analog and digital products, and collaborative software to consolidate and distribute information gaps in current practices exists.

One of the first gaps in current MDMP practices is how staff receives and evaluates terrain throughout MA and COA comparison. The primary method for assessing terrain is through 2D analog and digital maps, which provide a birds-eye view of the AO and a limited perspective of the geographic terrain. While several tools allow the terrain to be viewed in 3D, these tools are only readily available to some WFFs, and, as a result, the preponderance of detailed planning is still conducted using 2D analog maps.

Second, WFF functions rely on numerous overlays on a 2D analog map to show the AO, enemy displacement, phase lines, maneuver corridors, engineer graphics, etc. Overlays displayed on analog maps need to be modified and refined continually as changes to the mission are made throughout MDMP. The complexity increases when subordinate units simultaneously conduct parallel planning with their higher headquarters and rely on the most up-to-date overlays and graphics.

Additionally, when staff members collaborate, the analog map is stationary and requires personnel to walk around it if a WWF wants to emphasize an area of interest. For example, if the Intelligence WWF intends to point out a maneuver corridor to the Movement and Maneuver WWF and the person is across the table, they will have a different perspective and need to walk around the map for clarification.

Lastly, when staff members brief the commander on recommended COA, most products staff are 2D digital imagery inserted into a PowerPoint presentation with digitized (scanned) analog maps and overlays as backup products. By only looking at the terrain in 2D versus a combination of 3D graphics, it is possible to misplace the units. 3D tools, however, provide superior forms of visualization, user interaction, and analysis. That also includes the ability of 3D tools to support fully immersive, interactive experiences and the application of a range of 3D tools while observing and interacting with the 3D environment and its objects.

J. CHAPTER SUMMARY

This chapter provides an overview of how the U.S. Army conducts ADM and MDMP currently. Additionally, the text discusses the complexity of military staff conducting MDMP throughout each step of that process. The chapter also elaborates on the use of some mission command systems and tools by staff sections to consolidate information and present it to a commander for a decision. Lastly, the text covers the gaps in current practices.

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IV. PROTOTYPE SYSTEM DESIGN AND IMPLEMENTATION

A. INTRODUCTION

This chapter describes the framework used to design and develop an AR prototype tool to support MDMP, the 3D terrain used for the virtual environment, and the AR HMD display technology. The prototype visualizes a contested WGC scenario with three different WWFs and allows a user to conduct a series of tasks for the optimal placement of military units. For example, the user must analyze and place infantry, artillery, and engineer units at the different river crossing sites in the face of an enemy threat and develop different COAs. The system prototype is designed to improve situational awareness and comprehension for a user and enhance the effectiveness of WWF's task-planning efforts. This research will assist in developing a further understanding of the technological framework needed to support MDMP.

B. FRAMEWORK

1. Why AR?

Implementing AR technology for WWFs use during MDMP can enhance decision-making and facilitate effective collaboration between staff sections. By utilizing the HL2 AR display device, information can be presented in a stereoscopic form and enable users' real-time interaction with the virtual terrain. In addition, AR technology can reduce the time and resources needed for multiple staff sections to create analog products used during traditional MDMP.

The see-through, head-mounted AR displays are more appropriate for multiple staff sections collaborating during MDMP for safety reasons—they allow users to maintain awareness of their physical surroundings while viewing 3D terrain. The ability to see other staff members is critical as WWFs constantly move around a map to analyze information, gesture to each other, and convey non-verbal forms of communication. In addition, a see-through AR display enables users to collaborate while remaining engaged with their physical surroundings.

Although a desktop computer may be an alternative solution to viewing information, it may limit access for other users.

2. Why Microsoft HoloLens?

Due to its capabilities and compatibility with other AR applications, the HL2 was chosen to project 3D terrain for the user. In addition, HL2 has excellent functionality to support the necessary gesture recognition because 3D information needs attentiveness of the eye and hand involvement. The user can keep the headset on, gaze through the transparent lens, see the elements of the surrounding physical world and synthetic 3D objects, or flip up the visor to see the physical world unhindered when he wants to transition from seeing AR to seeing only the physical world. Also, the HL2 does not require the headgear to be taken off when the visor is up or down; the wireless headset and battery allow the user to walk and interact with other users during the interactive session.

The multiple AR features in HL2 enable object manipulation, which is essential to our AR visualization system. In addition, the HL2 has much improved hand and eye movement tracking over the HoloLens 1. Participants who need to manipulate virtual objects can engage with them accurately thanks to this capability and the Mixed Reality Toolkit.

Comparing HL2 to other popular AR headsets, it was determined to be the most effective tool for completing the duties outlined in Chapter III, Task Analysis: Current MDMP Practices. Other headsets, such as Google Glass, are not truly an AR solution as they are monocular displays for smartphone use. Additionally, Google Glass lacks the tracking and motion controls necessary for manipulating digital objects in a virtual environment.

3. Why Unity and Microsoft Visual Studio?

a. Unity Software Engine

The AR visualization tool developed for this thesis was done in Unity, a popular game engine and development platform that allows the creation of real-time visual experiences for games and simulations. One of the primary reasons Unity was selected over

other game engines is that Unity supports multiple toolkits and assets that provide the required functionality and representation for viewing terrain in 3D and AR. In addition, the documentation for HL2 and free assets available in Unity helped address any issues with the graphic user interface (GUI) and development. That demonstrates the robustness of the Unity ecosystem and the resources available to developers who use it. In summary, Unity proved to be a suitable platform for creating the AR visualization tool, providing the necessary tools and resources for a successful project.

b. Microsoft Visual Studio

Jithu states that “Microsoft Visual Studio is an integrated development environment (IDE) used to develop applications for Windows, web, mobile, and cloud-based platforms” (Jithu, 2019). Some reasons why people choose to use Visual Studio include its comprehensive set of tools for coding, debugging, testing, and deploying applications, its features that help developers work more efficiently, its integration with other Microsoft tools such as Azure and GitHub, the community of developers is sizable and dynamic, offering assistance and exchanging information., and its ability to create applications for a range of platforms including Windows, macOS, iOS, Android, and Linux (Jithu, 2019). Overall, Visual Studio is a powerful tool that makes the development process easier and more efficient.

4. Hardware

The following hardware environment was used for the development of the AR visualization prototype tool:

- Microsoft HoloLens 2 device
- Alienware 17, 8th Generation Intel® Core™ i7-8750H, 32GB RAM, GTX 1080Ti Laptop

C. SIMULATION ENVIRONMENT

1. System Architecture and Initial Design

The architecture and idea for this project came from previous work conducted by Johana Cruz and JaMerra Turner for displaying a naval communication architecture through Unity (Turner & Cruz, 2022). The diagram presented in Figure 23 illustrates the necessary components for constructing a prototype in a 3D interactive AR environment. As mentioned earlier, the laptop utilized Unity software to generate 3D models within the environment. Then, the virtual scene was projected into the HoloLens 2 using the Mixed Reality Tool Kit (MRTK) and its corresponding Holographically Remoting feature. A Microsoft account was also established to utilize the Microsoft Holographic Remoting Player App, which was first installed on the HoloLens 2 headset. The IP address of the headset was subsequently linked with Unity's MRTK Holographically Remoting feature to connect and project the 3D environment from the laptop to the HoloLens 2, as seen in Figure 22.

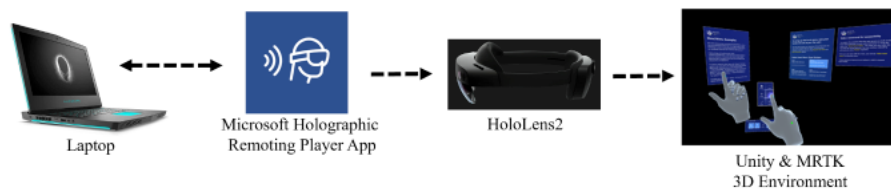


Figure 22. Components of simulation. Source: Turner and Cruz (2022).

2. Microsoft Holographic Remoting Application

The Holographic Remoting Player application is designed to link PC apps and games, facilitating live streaming of holographic content to the Microsoft HoloLens via a Wi-Fi connection. The feature is integrated within the MRTK, enabling Unity to connect with the HoloLens Holographic Remoting Player app via an IP address (*Holographic Remoting Overview—Mixed Reality*, 2022).

3. MRTK Mixed Reality Tool Kit

MRTK comprises a series of software packages that facilitate the creation of Mixed Reality applications across multiple platforms. Additionally, it offers assistance for various Mixed Reality platforms and hardware (*Mixed Reality Toolkit Packages*, n.d.).

a. Audio and Speech Controls

The HoloLens 2 has a microphone array comprising five channels and speakers with built-in spatial sound, enabling audio and speech functionalities. However, this thesis has chosen hand and eye-tracking as the most practical and straightforward input technique.

b. Actions and Gestures within HoloLens 2

Identifying hand movements related to specific actions and gestures involves the analysis of hand gestures using various tracking techniques such as head tracking, eye tracking, six degrees of freedom (DoF) tracking, spatial mapping, and mixed reality capture within the HL2. Some examples of actions include touch, hand ray cast, gaze, and air tap. At the same time, gestures such as selecting a button, hologram, moving a hologram, rotating a hologram, and changing the size of a hologram are illustrated in Figure 23.

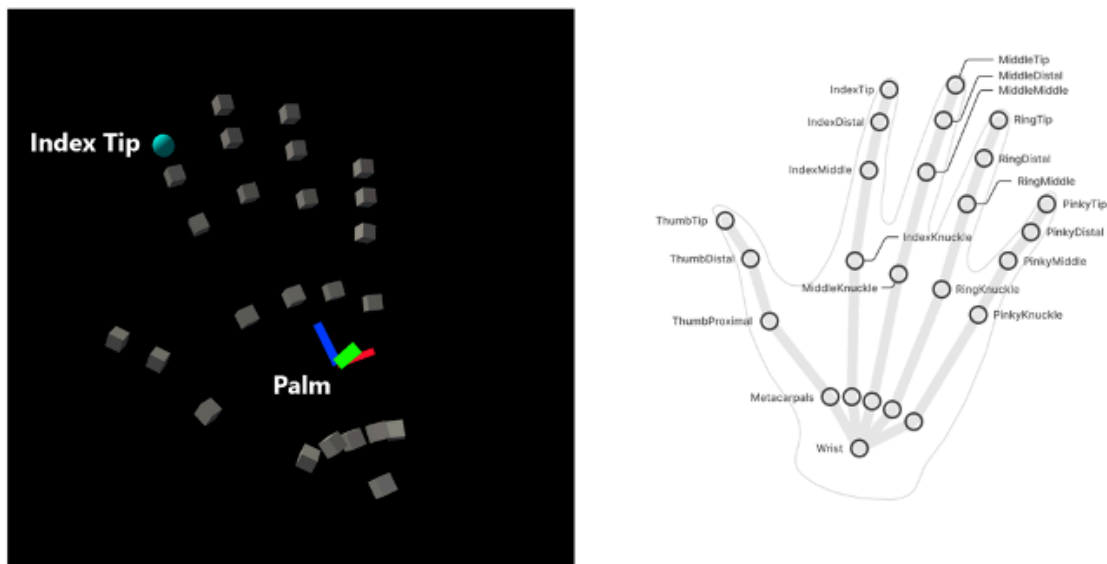


Figure 23. Hand tracking sensors. Source: Hand Tracking—MRTK 2 (2022).

D. 3D MODELS AND TERRAIN

1. Height Maps for Virtual Terrain

A height map is a digital image containing information about the altitude of a surface or terrain. It is widely utilized in computer graphics and video game development to produce realistic 3D models of landscapes and terrains (UE4, 2020).

Typically, a height map is a grayscale image in which the brightness of each pixel corresponds to the elevation of that specific point on the surface. Brighter pixels indicate higher elevations, while darker pixels indicate lower elevations (UE4, 2020). By mapping the range of brightness values in the height map to a range of heights, a realistic 3D representation of the terrain can be created.

To extract real-world terrain data and export it into the Unity Software Engine, the website <https://heightmap.skydark.pl/> was used for this project (Skydark, n.d.). The website is an open-source platform that provides a view of the world, and users can select any terrain, generate a height map, and export it as a .png file for uploading into Unity. In addition, users can customize the height maps to suit their needs as required. Figures 24 and 25 demonstrate how users can generate and customize height maps using the website.

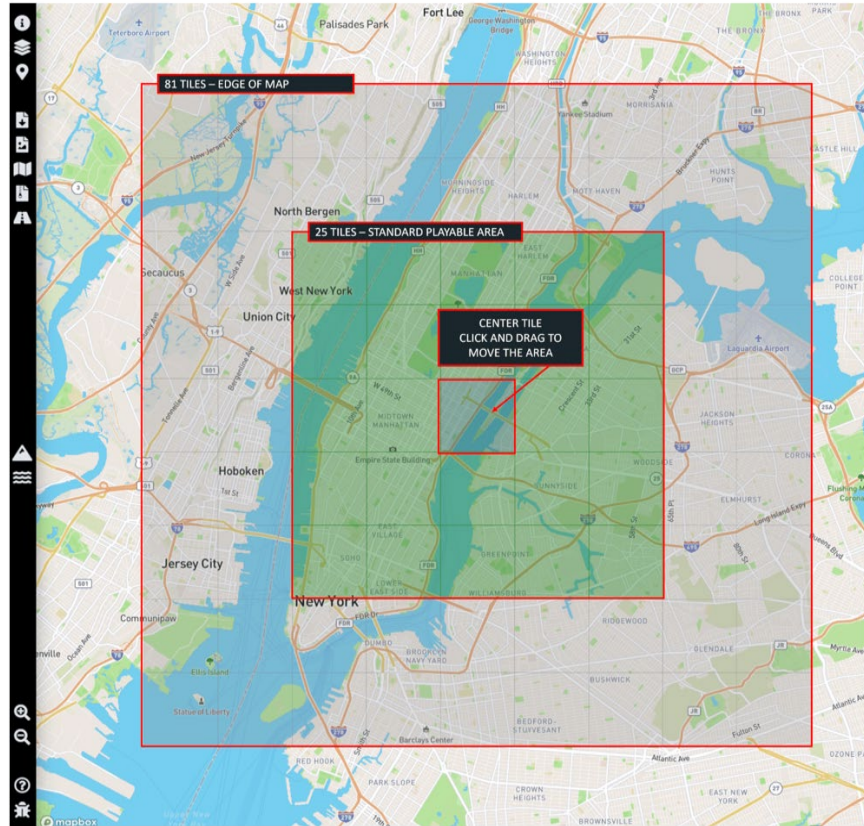


Figure 24. Height map example. Source: Skydark (2022).



Figure 25. Exporting height map into Unity. Source: Skydark (2022).

2. Building 3D Terrain

Following the export of the terrain to Unity, it is necessary to modify the landscape, as the imported terrain is monochromatic. Modifying the terrain is achieved by utilizing a terrain asset tool kit, which can be downloaded free of charge from the Unity Asset Store. This tool kit empowers users to manipulate the terrain within the scene, allowing for features to be added, raised, or lowered as necessary. Furthermore, textures can be added to reflect diverse vegetation across the terrain, effectively increasing its visual appeal.

This project incorporated five different terrain textures to create a more realistic representation of the terrain based on its real-world counterpart. The outcome of this endeavor was a landscape that was no longer monochromatic but boasted a richness that conveyed the distinction between grasslands, roads, rocks, sand, and water. The addition of terrain textures is a well-known technique employed in 3D modeling and game development to create realistic environments. Figure 26 represents the terrain used in this project after its modification using the terrain tool kit.

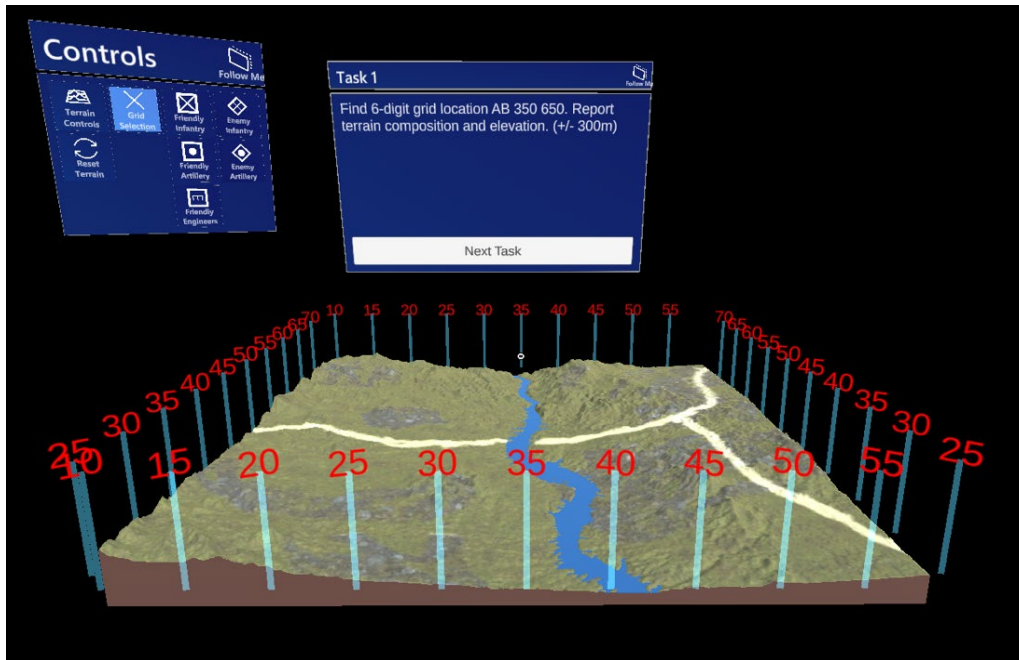


Figure 26. Virtual terrain when viewed through Unity.

E. GRID COORDINATE SYSTEM

Utilizing a military grid coordinate system was crucial for accurate, domain-specific identification of grids, extraction of pertinent terrain data, measurement of distances between points, and computation of slope angles between disparate locations. A combination of game objects, colliders, and computer scripts were employed to achieve these functionalities. These scripts, which were developed using Visual Studio, facilitated the implementation of the grid coordinate system. The following scripts were created through Visual Studio for the grid coordinate system:

1. Gridcell (Appendix A)
2. Gridinterdict (Appendix B)
3. Gridlabels (Appendix C)

To extract a grid from the 3D terrain, two different functions within the HL2 were created to quickly acquire terrain information. Hand-tracking was not a suitable option for this project as the hand-tracking only worked on a parallel surface which resulted in grids not being acquired as the 3D terrain is not flat. The solution for this problem was using

gaze-tracking from the HL2 to the terrain. Gaze-tracking allows users to look anywhere on the map and acquire a grid. Next, a hand gesture was created through HL2, allowing the user to conduct a “pinching” gesture with their pointer finger and thumb. Combining the two features of gaze-tracking and pinching allowed the user to look anywhere on the map and pinch to acquire a grid. Figure 27 shows how a user can look at the 3D terrain, conduct the pinching gesture, and acquire a grid.

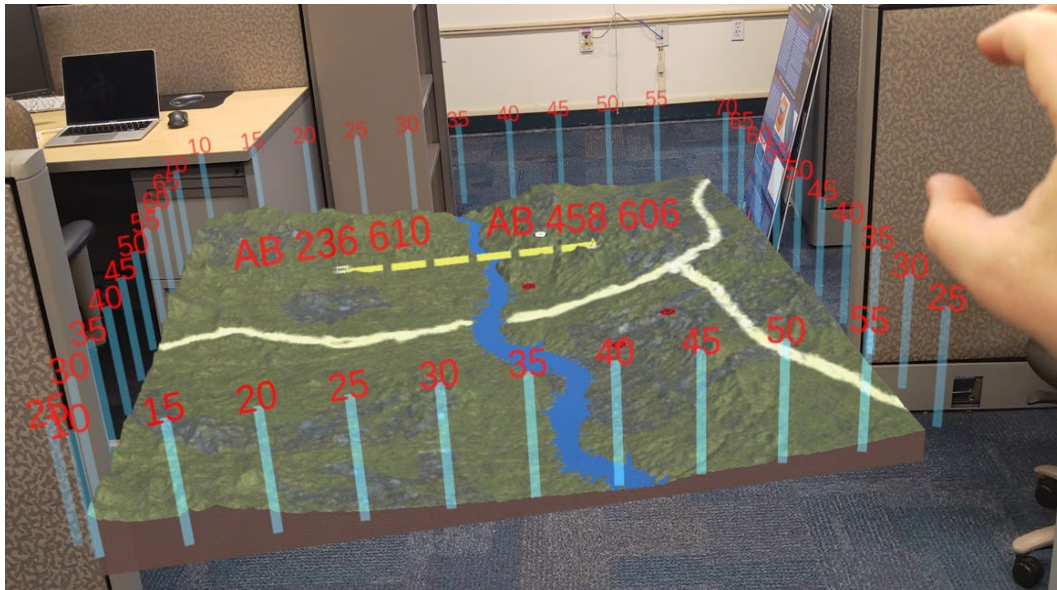


Figure 27. Gaze-tracking and pinching gesture to acquire a grid.

For this project, I imported terrain data spanning a 50x50 kilometer area. Game objects representing grid identifiers were strategically placed around the map at intervals of 5 kilometers for the Easting and Northing coordinates. The grid identifiers enable users to quickly identify a four-digit grid’s general area. Using the grid coordinate system, users can look at the 3D terrain and find the general location of a grid. To locate an exact six-digit grid, the user can conduct the pinching gesture, and semi-transparent red numbers displaying the 6-digit grid will appear above the desired grid, as shown in Figure 28.

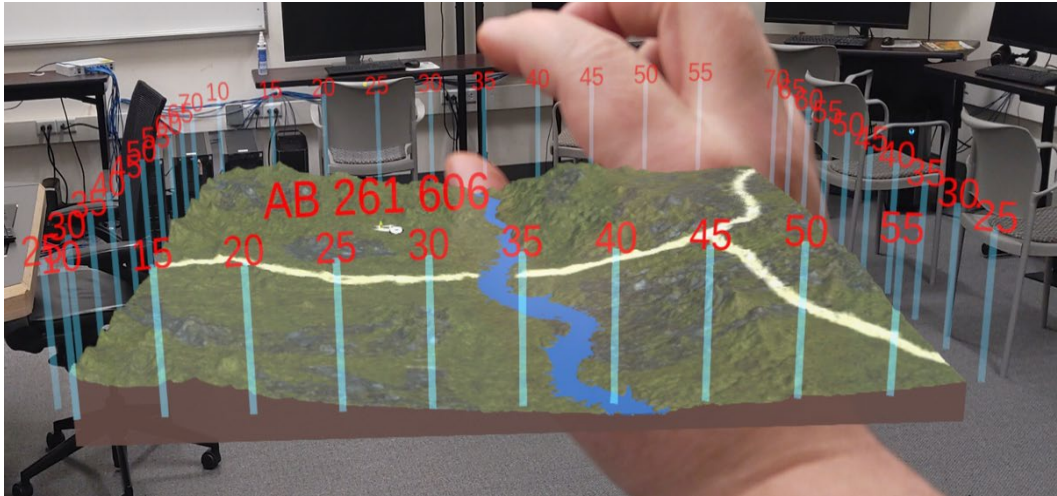


Figure 28. Grid coordinates displayed in HL2.

An additional feature was incorporated, enabling users to obtain terrain information between two grids. That feature utilizes the same capability mentioned previously for gaze-tracking and a pinching gesture—users need to perform the pinching gesture and direct their gaze toward the two desired grids. Once achieved, a GUI interface titled “Terrain Information” will appear, presenting users with essential details such as the two grids, the distance between them, elevation, terrain composition, and slope. This feature has been included to cater to the specific needs of military planners, who often require additional terrain information to ensure the efficient deployment of equipment.

F. HEADS-UP DISPLAY (HUD) INFORMATION PANELS

The GUI consists of three parts. The first part is a control panel that facilitates user interaction with a virtual landscape and placement of the military units. The second part of the GUI is the terrain information that displays terrain composition and grid information from either a single point or two points. Lastly, the third GUI part was a bar that presents the active task and, upon successful completion, permitted the user to advance to the next task.

All GUIs were designed with a blue semi-transparent background and a white border. The component is accentuated in white as the user hovers over a GUI, enabling them to identify their selection. Additionally, the GUIs have a feature that allows users to

move them by pinching the borders. Due to the limited field of view (FOV) of HL2, relocating the GUI is necessary to enable users to view both the terrain and GUI simultaneously. Finally, an audio cue is triggered when the user pinches any location on the landscape or within a GUI, providing audible confirmation of their selection within the scene.

1. Control Panel

The control panel is composed of three components which allow the user to find different grids and terrain composition, scale and rotate the terrain, and select different military units for placement. Figure 29 shows how the control panel is displayed within HL2.



Figure 29. Control panel.

a. Terrain Details

The control panel is comprised of various components, the first being the “*terrain details*.” Upon activation, this component offers two distinct functions. The first function enables the user to (pinch) and obtain precise information such as grid coordinates, elevation, and terrain composition by simply tapping anywhere on the terrain. Furthermore,

users can also hold the (pinch) between two different grid coordinates to obtain the distance between the points, slope, elevation difference, and terrain composition. When terrain detail is active, a separate GUI labeled terrain information is displayed when a user wants to acquire knowledge in a single grid or between two points. The terrain details GUI provides comprehensive data regarding the selected points, making it a valuable tool for the user.

b. Rotate Map

The control panel's second component has the label "*rotate map*," and is comprised of three distinct functions that allow the user to manipulate the terrain by rotating, scaling, and rotating the 3D landscape. The ability to rotate the 3D terrain is an invaluable feature facilitating staff collaboration, enabling multiple users to view the terrain from diverse perspectives. Consider, for instance, the Fires WWF, which seeks to identify the optimal position for artillery placement. The *rotate map* feature empowers the WWF to pivot the map, enabling them to make their point more effectively.

Upon activating the "*rotate map*" function, the user is presented with multiple handles at specific locations on the 3D terrain. These handles enable the user to manipulate the position of the landscape effortlessly. For example, at the very center of the terrain lies a circular object, which comes to life as soon as the user taps and holds it. Doing so gives the user the power to raise or lower the terrain on the Y-axis.

Furthermore, the map's corners house both square and circular virtual objects. Tapping and holding on to the square objects allows the user to either increase or decrease the size of the 3D terrain. Lastly, the circular virtual object can be activated by tapping and holding it, allowing the terrain to be rotated along the X and Z axis. The "*rotate map*" features enable the user to remain stationary while effortlessly manipulating the landscape (Figure 30). The last feature of the "*rotate map*" component is a feature labeled "*reset map*," which allows the user to reset the map to its original position.

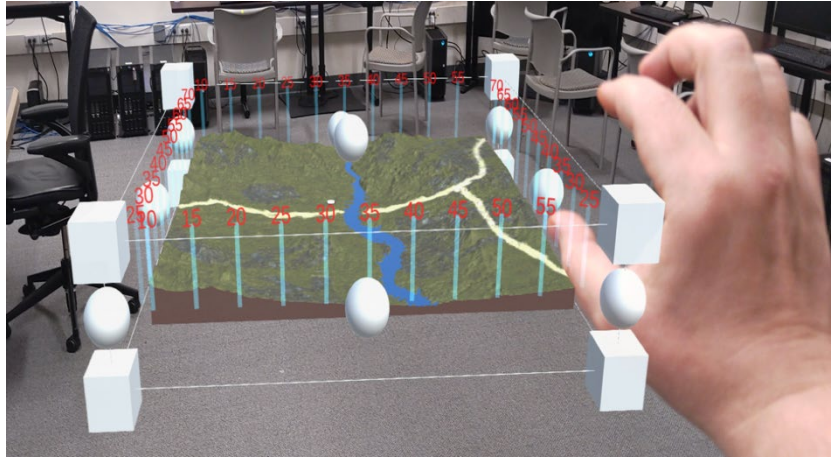


Figure 30. Rotate map component.

c. Military Units

The control panel offers a comprehensive suite of features, including the highly advantageous “*Military Units*” component. This feature lets the user view three types of friendly military units: infantry, artillery, and engineers. Moreover, users can effortlessly tap and select prepositioned enemy infantry and artillery units adjacent to the friendly army units. By utilizing these capabilities, the user can swiftly and efficiently locate, evaluate, and strategically place military units in the optimal position during a contested WGC scenario (Figure 31).



Figure 31. Military unit components.

Upon selecting the infantry component, the user has six distinct, pre-determined battle positions embedded within the 3D terrain. The user can then evaluate each position by tapping on it. In addition, the terrain information GUI is activated upon selecting a battle position. It displays crucial information, such as cover and concealment, based on the enemy's line of sight from across the river.

Furthermore, once the user is selected a battle position, direct and indirect fire range rings encompassing the battle position game object become visible. These range rings provided information about whether the enemy forces can be ranged from the selected battle position. By leveraging these two features, the user can optimally place each unit to provide support for a WGC. Finally, after analyzing all six pre-determined battle positions, users can select a desired position to place an infantry unit by double-tapping (Figure 32).

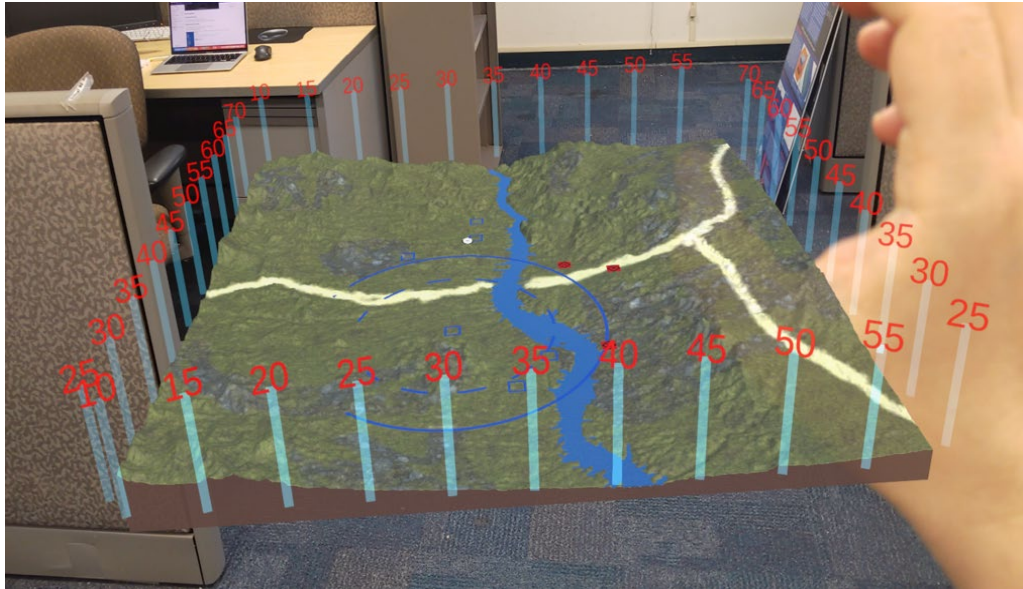


Figure 32. Infantry unit six battle positions.

Upon activation, the artillery unit selection exhibits feature akin to those of the infantry unit component. Specifically, when selected, three distinct Position Artillery Areas (PAAs) game objects manifest within the 3D terrain. The user can evaluate each PAA and the terrain information GUI offers identical data on cover and concealment. Furthermore, activating this feature triggers the appearance of an indirect fire range ring on each PAA. This functionality allows the user to assess each PAA thoroughly and place the artillery unit strategically to optimize coverage while also enabling them to range enemy units with precision (Figure 33).

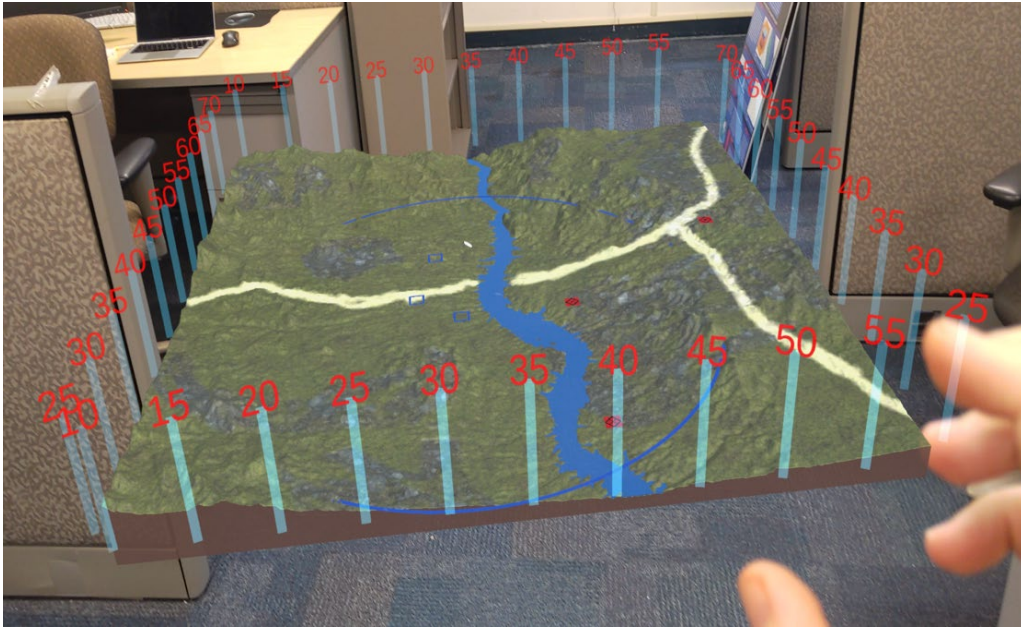


Figure 33. Artillery unit three PAAs

The activated engineer military unit component has been deployed to display three prepositioned crossing sites supporting the WGC scenario. The user is granted the capability to select each crossing site, and the terrain information GUI presents essential parameters such as width, depth, and current for each location. After carefully analyzing the potential crossing sites, the user can double-tap on the most suitable place and designate it as the position for the engineer unit's deployment (Figure 34).

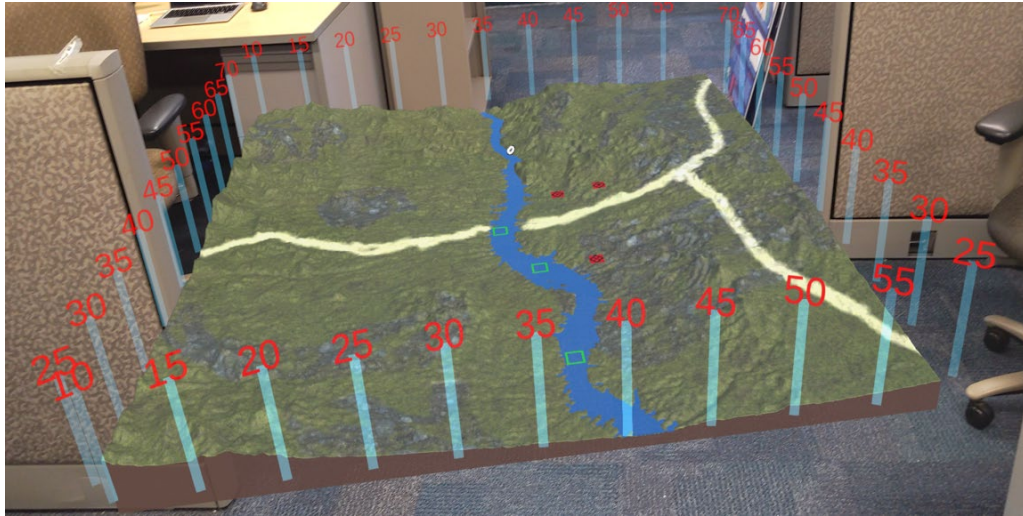


Figure 34. Engineer unit three river crossing sites.

In conclusion, including enemy unit components designed for infantry and artillery enables the user to assess two distinct infantry units and one artillery unit. When selecting enemy infantry or artillery units, range rings for indirect and direct fire capabilities are displayed around the chosen unit. This innovative feature permits the user to analyze the locations of enemy forces and determine the extent of their weapons' reach, which may consequently affect the placement of friendly forces (Figure 35).

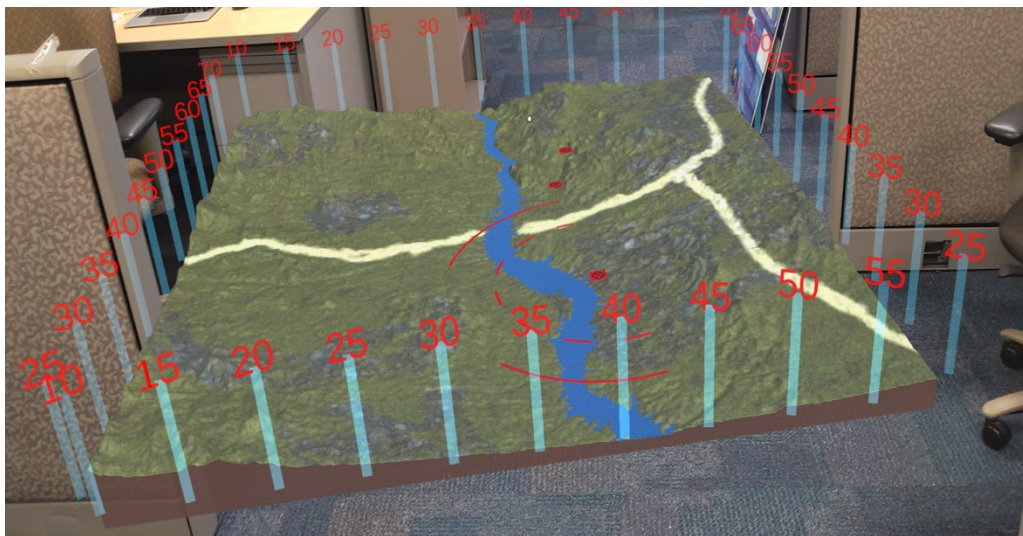


Figure 35. Enemy unit component.

2. Terrain Information GUI

The GUI for terrain information is shown upon the user's selection of the terrain details component and upon performing a single (pinch) or holding the (pinch) between two points on the terrain (Figures 36 and 37).

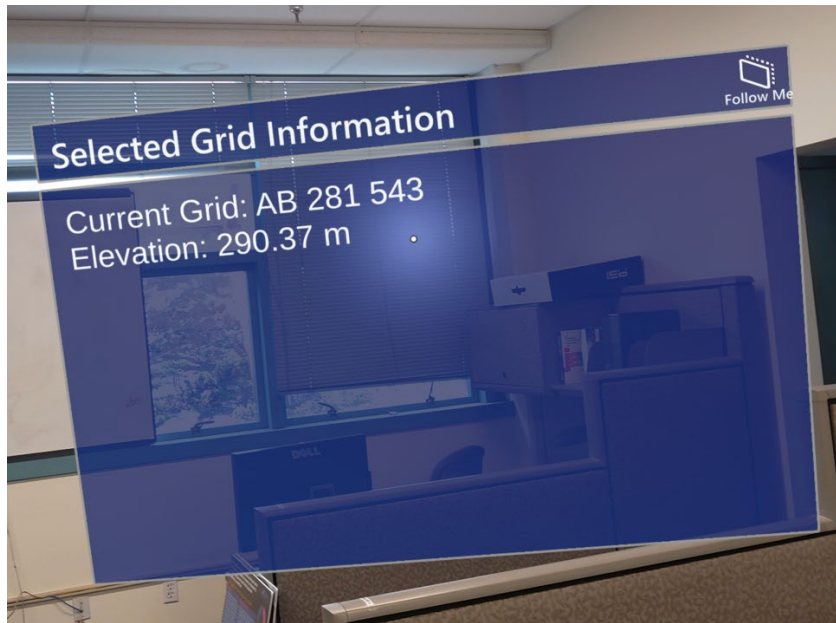


Figure 36. Terrain information GUI for a single (pinch).

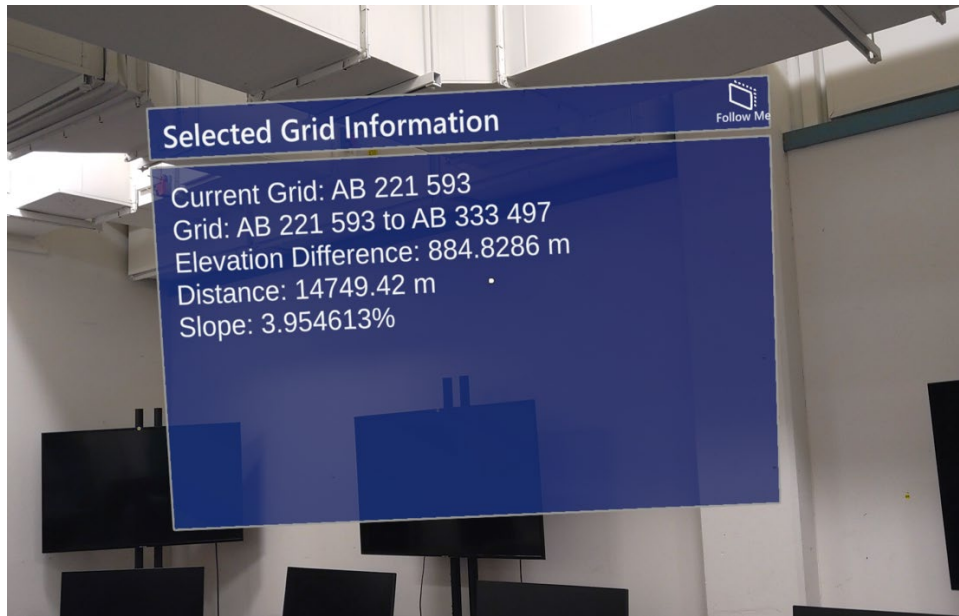


Figure 37. Terrain information GUI for hold the (pinch) between two points.

3. Taskbar GUI

The taskbar is a GUI that displays the current task instructions and allows the user to proceed to the next task upon completion. For this experiment, there are a total of 8 different tasks (Figure 38).

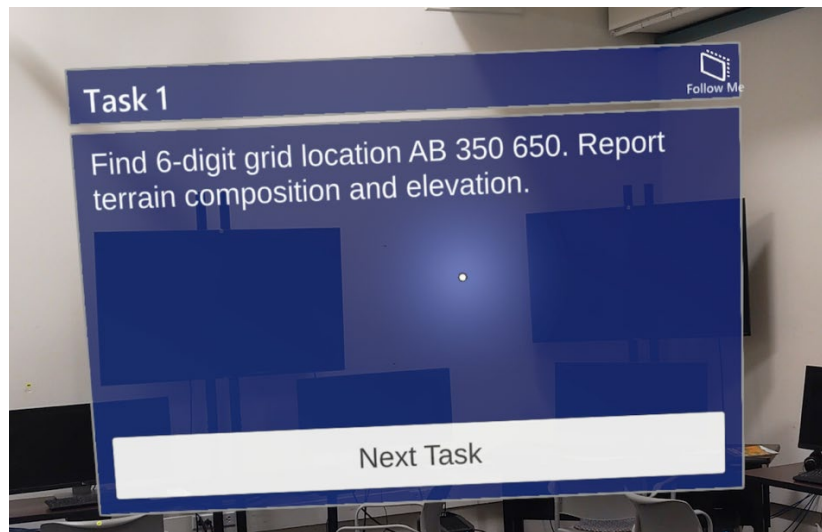


Figure 38. Taskbar example.

G. TASK USER INTERFACE

Eight distinct tasks were created to assess the prototype’s functionality and usability. Tasks 1–2 focus on evaluating the usability of the grid coordinate system and measuring the distance between two points. Task 3 asks the user to use the rotate map feature to raise, lower, scale, and rotate the terrain. Tasks 4–6 provide the user with an opportunity to assess three different army units: infantry, artillery, and engineers, by analyzing their respective components and determining the best position for them in a contested WGC scenario. Task 7 enables the user to compare the threat posed by the enemy with the friendly army units. Finally, Task 8 unlocks all the prototype’s features and presents the user with a challenging WGC scenario where they must position army units to support the optimal river crossing site while facing the risk of enemy fire.

1. Task 1: Find 6-digit grid location.
2. Task 2: Report distance between two points.
3. Task 3: Rotate Map.
4. Tasks 4–7: Report information respective to each WWF and enemy.
5. Task 8: WGC scenario.

H. CHAPTER SUMMARY

This chapter examines the selection of hardware and software platforms for the prototype, providing insight into the reasoning behind the choices made. Moreover, the chapter delves into the intricate process of creating and exporting the 3D terrain into Unity and showcasing its seamless display in HL2. The implementation of the grid coordinate system and the various graphical user interfaces utilized to navigate between tasks are also explored in detail. Lastly, the chapter sheds light on the eight tasks assigned to users to assess the prototype’s functionality.

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V. USABILITY STUDY

A. INTRODUCTION

The effectiveness of the AR visualization tool is based on the data sets collected in the usability study. The AR visualization prototype tool allowed importing heightmaps and transforming the terrain into 3D to support decision-making during MDMP. In addition, the system visualized a contested WGC and the potential placement of military units, allowing participants to review possible unit placement and make informed decisions.

The AR-based system provided a “real-time” representation of a contested WGC, and it allowed the user to analyze terrain without limiting current practices and comprehending how military plans for a WGC. The feedback from participants in the usability study was used to generate new ideas and additional ways the system could benefit the WWFs recommending COAs to a military commander.

Overall, the usability study provided valuable insights into the effectiveness and potential benefits of the AR visualization tool. The study demonstrated that the AR-based system was an efficient way of presenting complex data and supporting decision-making. The suggestions for future work will help to develop the system further and improve its usability and effectiveness.

B. INSTITUTIONAL REVIEW BOARD (IRB) PROCESS

To conduct research involving human subjects, NPS requires that the study undergoes an Institutional Review Board (IRB) process. The IRB committee reviews the research proposal and related documents to ensure the study is conducted ethically and per legal and regulatory requirements. The following documentation was submitted for the approval of the NPS IRB committee:

1. IRB Application
2. Scientific Review Form
3. Conflict of Interest Disclosure Form

4. Informed Consent Form
5. Recruitment Flyer (Appendix D)
6. Recruitment Email
7. Simulator Sickness Questionnaire (SSQ) (Appendix E)
8. System Usability Scale (SUS) Questionnaire (Appendix F)
9. Demographics Questionnaire (Appendix G)
10. Post-Task Questionnaire (Appendix H)

After submitting the required documentation, we were approved to begin the usability study in May 2023.

C. STUDY DESIGN

1. Physical Environment

The research was conducted in a supervised setting, specifically in NPS's Modeling Virtual Environments and Simulation (MOVES) Institute. The grey tape on the floor indicates each applicant's starting position for the experiment. (Figure 39)

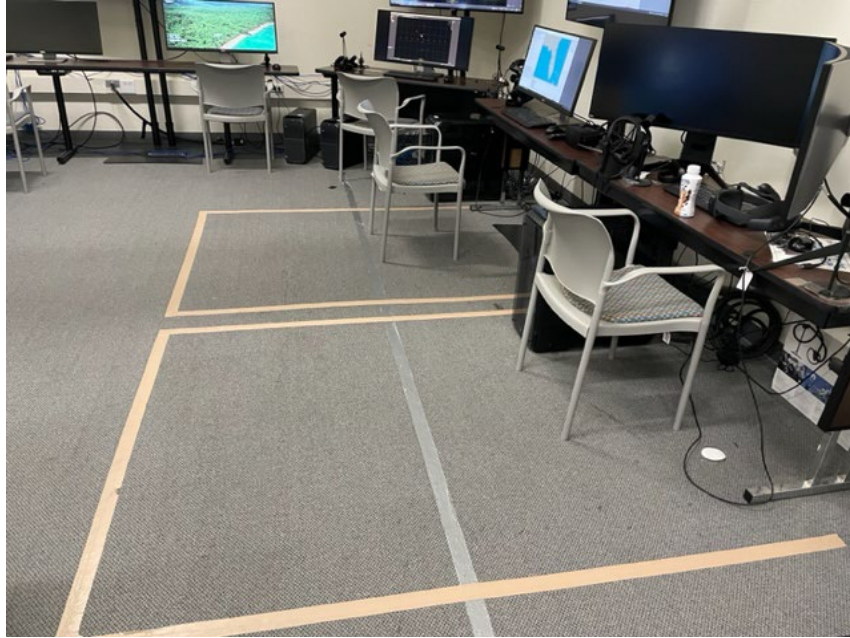


Figure 39. View of training area without HL2 headset.

2. Training Environment

Throughout the study, participants were introduced to a cutting-edge virtual training environment known as H-Tips, as depicted in Figures 40 and 41. The overarching goal of this immersive setting was to familiarize participants with the rich array of features offered by the HoloLens 2 headset and the diverse range of user techniques available to them. Key among the methods required to complete the study tasks was gaze-casting, ray-casting, and air-tapping (pinching) gestures.

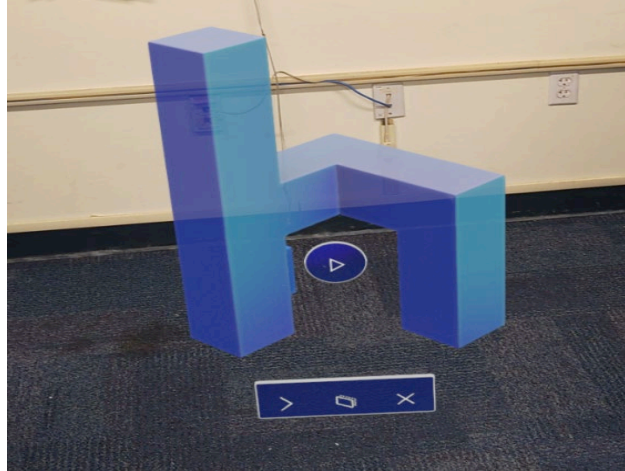


Figure 40. The H-Tips application.

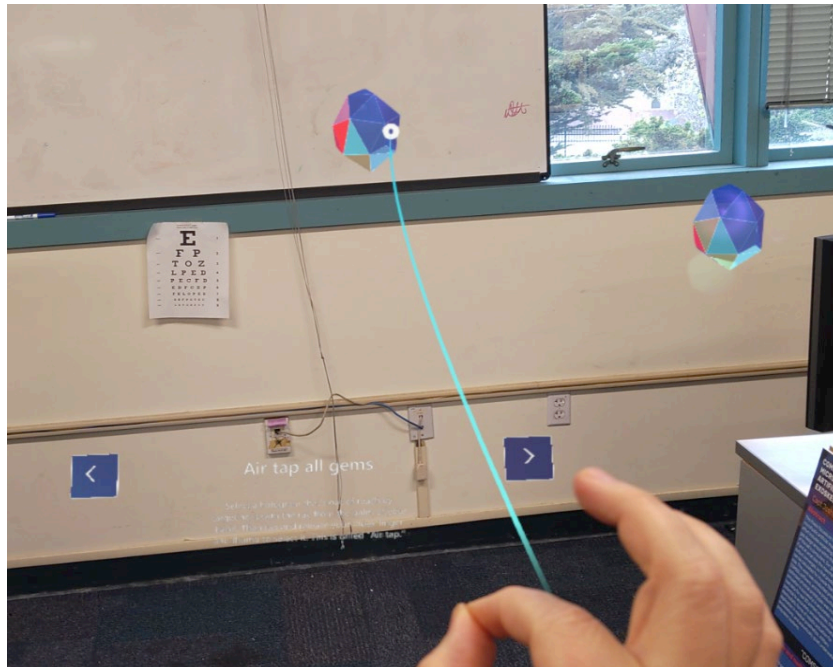


Figure 41. Ray-Casting and selecting an object in H-Tips.

3. Terrain Visualization Tasks

Each participant was expected to complete eight tasks. The study aimed to include participants from all military service branches, and their rank was deemed immaterial. However, to ensure that all service members could effectively complete the tasks, everyone was provided with a sheet containing information on how to read the Military Grid

Coordinate System and the meaning of different military symbols in the virtual environment needed to complete all tasks. That approach was taken to prevent any disadvantage for service members who may have lacked familiarity with these essential skills. Additionally, by providing all participants with the necessary resources to comprehend the military grid coordinate system and military symbology, the study collected accurate data without introducing any confounding variables related to prior experience or knowledge.

4. Collection of Objective Data Set

The objective data set was derived from the system's reports; it consisted of time-stamped system event logs about participant's interactions with the menu items and objects in the virtual environment. Once the participant selects "Task 1," the system event log file records these interactions in an Excel data file format. These logged interactions include all menu item and object interactions until the participant exits the application after initiating the "Task 1" button. The event log file is saved upon task completion at the completion menu (Figure 42). The combined data logs for each participant were used to analyze the data collected from all participants and obtain summative information.

The event logs consist of the following data:

- Time when a task starts / ends.
- Time for the start and end of each object manipulation (translation, rotation, scaling, grids, and evaluating positions), along with the specific ID for each interaction.
- Time stamps of menu selections.
- Time stops when participant "pinches" next task.
- Total time on each task.

Event-Log-Task-8.04-30-2023-102514

0	start-time	10:19:49
0	Start Task	8
76.8752648	Crossing Selection Toggled	
96.8235544	Grid Selection Toggled	
101.4915569	Grid Cell Selected	AB 336 501
103.6120668	Second Grid Cell Selected	AB 360 506
126.3733593	BP Selection Toggled	
157.6759065	Unit Selected	BP 1
190.3269963	Unit Selected	BP 2
224.1785575	Unit Selected	BP 4
239.2122463	Unit Selected	BP 5
250.4675062	Unit Selected	BP 6
264.9776811	PAA Selection Toggled	
273.6741674	Unit Selected	PAA 1
298.8633545	Unit Selected	PAA 3
303.7615365	Unit Selected	PAA 2
324.780205	End Task	8
324.780205	end-time	10:25:14

Figure 42. An example of the event log.

5. Collection of Subjective Data Set

A series of questionnaires were utilized to gather subjective data. The primary method for collecting subjective data was using the Qualtrics software system, an online platform that allows the experimenter to enter all questionnaires online, consolidates responses from applicants, and provides statistical analysis of the results. Additionally, paper copy was available if the internet connection went down, and a user could not use Qualtrics. Finally, all the information collected from the participants was entered into an Excel spreadsheet for further analysis.

Four different questionnaires were used to capture subjective data:

- Pre-task, and post-task Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993)

- System Usability Scale (SUS) (Brooke, 1995)
- Demographics questionnaire
- Post-Task Survey

D. PROCEDURE

Each participant was trained on H-Tips and taught how to read grid coordinates and military symbology. In addition, the experimenter was available to guide them as needed during the training session, which took approximately 15 minutes to complete.

After the training session, participants started executing eight tasks in a virtual terrain environment. During the tasks, the experimenter refrained from providing any guidance, and participants had to rely solely on the instructions provided within the virtual environment to complete each task. If a participant encountered difficulties or could not complete a task, the experimenter established a remote IP address to inspect visually what the participant was seeing inside the HL2.

To further analyze the participants' performance, the experimenter instructed them to verbally communicate their answers to each task's question, read aloud, and express their thoughts, which were recorded on video. The completion time for each task was not restricted.

The following was the estimated time for each participant:

- Participant given a short brief about the study (2 minutes).
- Brief on Informed consent (5 minutes)
- Baseline Simulator Sickness Questionnaire (SSQ) (2 minutes)
- Training: Familiarization with HoloLens 2 headset and user interface. Participant is asked to complete training using H-Tips and read script for military grids and military symbology (15 minutes)
- Instructions for the main experiment (2 minutes)

- Experiment: eight tasks (30 minutes).
- Post-task simulator sickness questionnaire SSQ (2 minutes)
- Post-task survey and SUS questionnaire (2 minutes)
- Demographics questionnaire (2 minutes)
- A short back brief and answer any questions (5 minutes).

E. PARTICIPANTS

The study involved 16 participants hailing from various branches of service; the study was set out to include a minimum of 15 and a maximum of 40 participants for this usability study, and ultimately 16 individuals took part in the experiment. To ensure a diverse and representative sample of officers from different branches and ranks, the recruitment efforts were extended to all students at the Naval Postgraduate School and faculty. The recruitment process included email correspondence, a flyer (see Appendix D), and direct communication with peers.

1. Demographics Questionnaire

The Demographic questionnaire was designed to obtain specific information from each participant regarding their background and experience with AR or VR HMDs. It began with general questions about their gender, rank, and branch of service, followed by more detailed questions about their experience as a staff member involved in mission planning and their specific role in that position. Finally, the questionnaire inquired whether the participant had any previous experience with AR or VR, either personally or professionally. The purpose of this questionnaire was to gain a comprehensive understanding of the participants' backgrounds in mission planning and their prior experience with AR or VR technology. A total of 16 participants participated in the usability study, with 15 being male and one being female. (Table 1)

Table 1. Participants' gender (Demographics questionnaire, Question 5).

	Gender
Female	1
Male	15
TOTAL	16

The study involved diverse individuals with varying ranks ranging from O-2 to O-5 and NPS faculty representation from all branches except for Space Force and Navy (Figure 43). In Figure 44, there is a discrepancy where one applicant accidentally selected the Navy as their branch but is an NPS faculty member. The years of service among the participants was 6 to 32 years, with an average of 12.5 years, as detailed in Table 2.

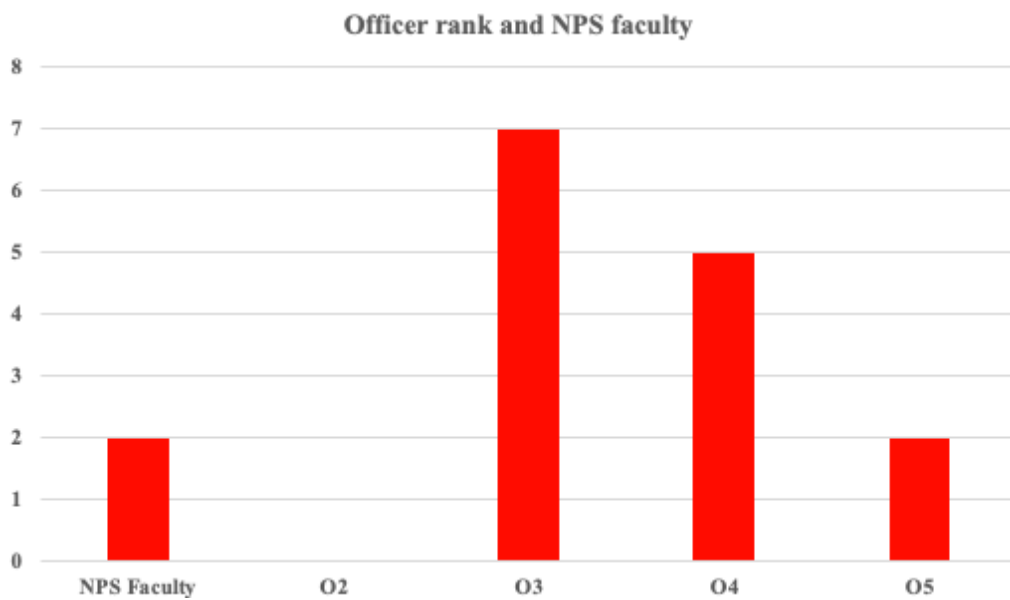


Figure 43. Participants' current military rank (Demographics questionnaire, Question 3).

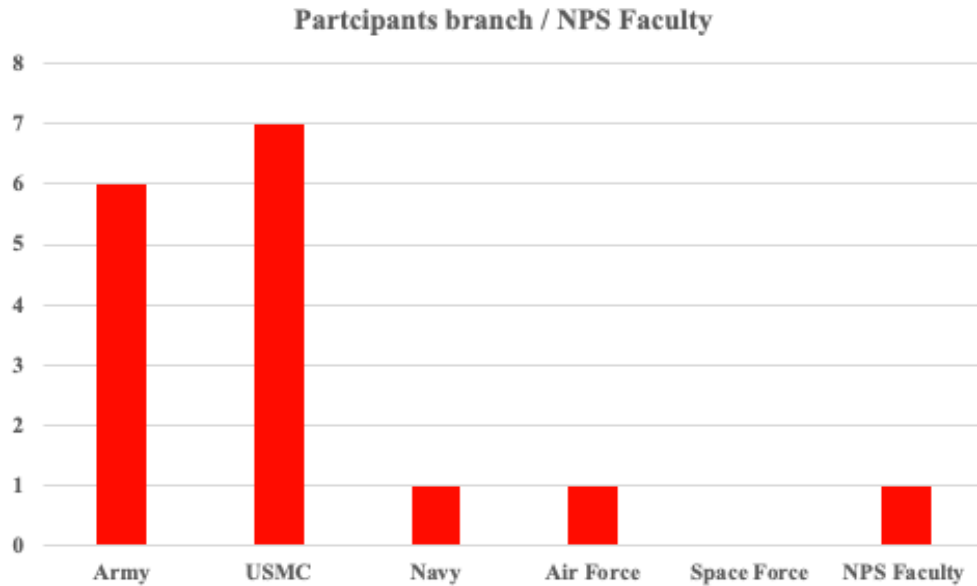


Figure 44. Branch of service (Demographics questionnaire, Question 6).

Table 2. Years of service.

	Years of service
Average	12.5
Min	6
Max	32
St. Dev.	6.5

2. Demographics Questionnaire: Experience

After collecting data from a cohort of individuals, their prior experience was analyzed to ascertain their involvement in mission planning. For those who had engaged in mission planning before, it was further inquired about the nature and extent of their participation and the role they held. From the gathered data, Figure 45 demonstrated that 13 of the 16 participants had prior involvement in the mission planning process. Out of the 13 participants who participated in mission planning, 11 of the personnel were primary planners. In comparison, the other two participants observed a mission planning process but were not the primary or supplementary planners (Figure 45).

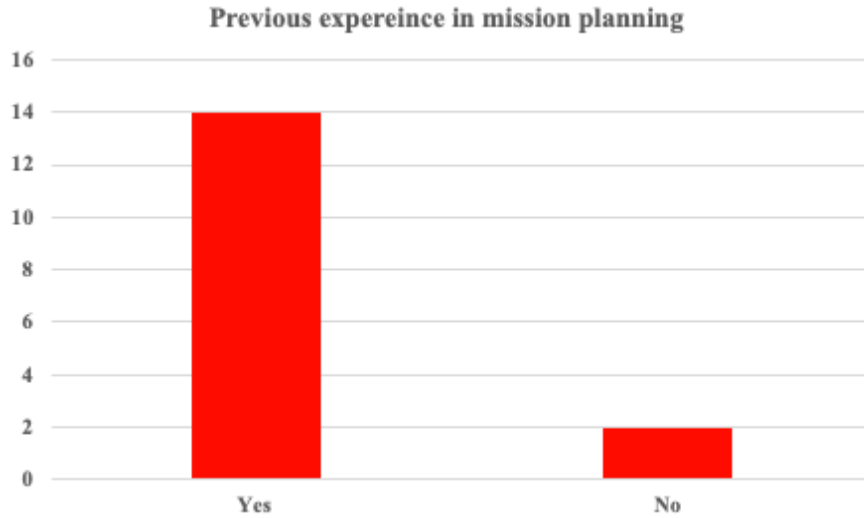


Figure 45. Prior participation in military planning process (Demographics questionnaire, Question 14).

Figure 46 indicates that most participants in the study were familiar with either AR or VR. However, upon analyzing the demographic data, it was found that two participants reported no prior usage of AR or VR HMDs, whereas 14 individuals reported having used AR or VR before. Among the 14 participants with previous experience with HMDs, nine had used these technologies for personal purposes, while the remaining five had used them for work-related reasons. The aim of assessing the participants' prior use of AR or VR HMDs was to determine whether their previous exposure to these technologies could impact their performance on the study's tasks compared to those with no prior experience with these systems.

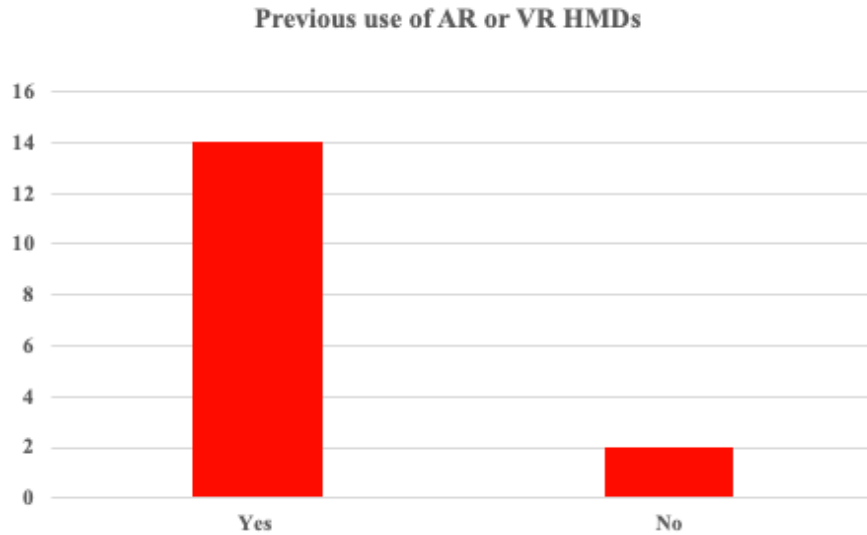


Figure 46. Previous use of AR or VR HMD (Demographics questionnaire, Question 11).

F. RESULTS

1. Objective Data Set

Upon analyzing the event logs, it was found that Task 8 required the most extended time compared to the first seven tasks, as depicted in Figure 47. The tasks were designed to increase complexity, incrementally building on the previous tasks. After completing the initial task, participants were more familiar with the environment, and subsequent tasks became less challenging. As a result, participants could typically identify and accomplish each task quicker than the last, as the instructions were similar, and the scene's functionality remained the same. The following list are the times to complete tasks 1–8:

1. Task 1: average = 152.04 sec, minimum (min) = 15.49 sec, maximum (max) = 471.88 sec, and standard deviation (StdDev) = 95.29 sec
2. Task 2: average = 97.78 sec, minimum (min) = 16.78 sec, maximum (max) = 198.20 sec, and standard deviation (StdDev) = 49.17 sec
3. Task 3: average = 130.34 sec, minimum (min) = 52.27 sec, maximum (max) = 242.28 sec, and standard deviation (StdDev) = 51.96 sec

4. Task 4: average = 236.62 sec, minimum (min) = 118.99 sec, maximum (max) = 477.79, and standard deviation (StdDev) = 105.16 min)
5. Task 5: average = 94.10 sec, minimum (min) = 35.89 sec, maximum (max) was 198.13 min, and standard deviation (StdDev) = 43.52 min)
6. Task 6: average = 84.10 sec, minimum (min) = 27.22 sec, maximum (max) was 179.72 sec, and standard deviation (StdDev) = 44.90 sec)
7. Task 7: average = 85.07 sec, minimum (min) = 20.79 sec, maximum (max) was 179.63 sec, and standard deviation (StdDev) = 39.95 sec)
8. Task 8: average = 315.62 sec, minimum (min) = 143.18 sec, maximum (max) = 557.02 sec, and standard deviation (StdDev) = 121.54 min)

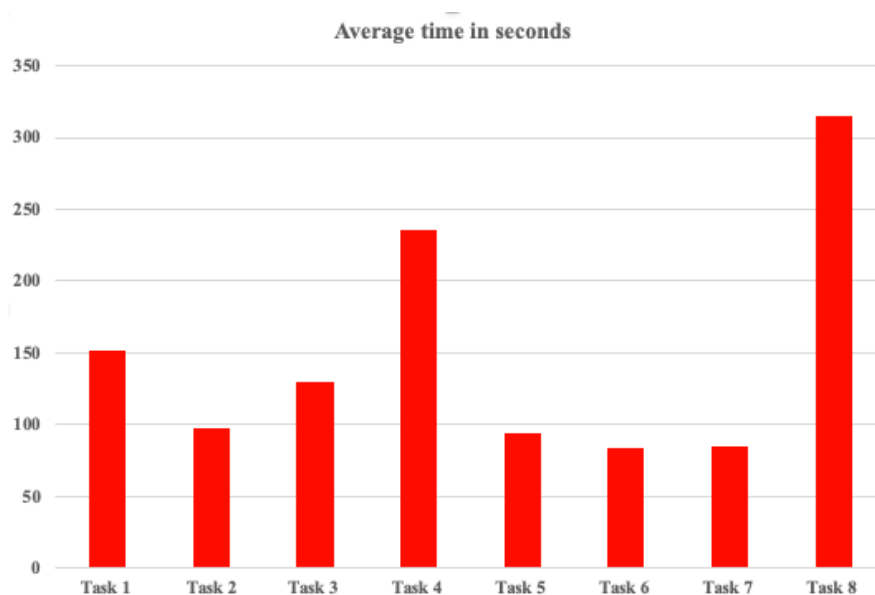


Figure 47. Participants' average time for the eight tasks in the VE.

Figure 48 depicts the average number of additional attempts made by participants to find a 6-digit grid in Task 1 and to measure the distance between two points for Task 2. The higher-than-anticipated number of attempts for both tasks can be attributed significantly to the gaze-casting technique. Participants located further away from the terrain tended to select the wrong grid due to slight movements in their gaze, resulting in

incorrect selections. Furthermore, participants tended to hold the pinching gesture for longer than the intended duration of 0.25 seconds while attempting to select a single grid. The system prototype was designed for users to choose a single grid within a quarter second of pinching. Holding the gesture for any additional time would trigger the system to measure the distance between two points resulting in an incorrect grid selection.

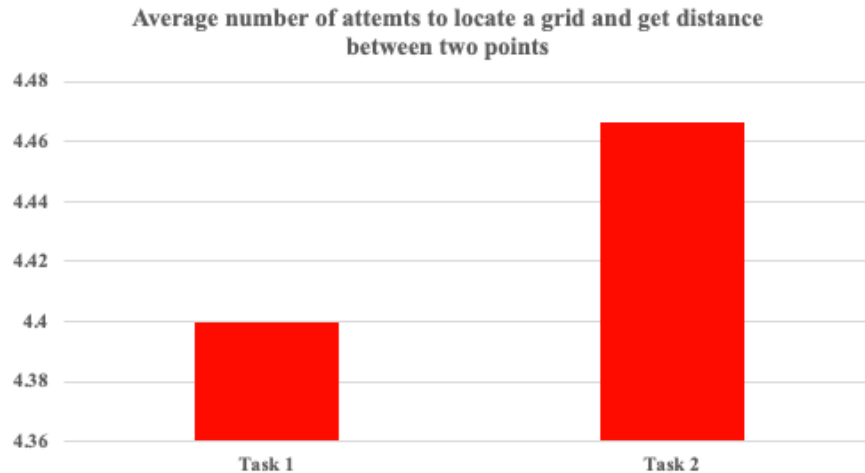


Figure 48. Average number of attempts for Task 1 and 2.

The chart labeled Figure 49 displays the number of additional attempts it took for applicants to transform the terrain. This specific task had one had the fewest mistakes made among the eight different tasks. Additionally, Table 3 presents the average number of attempts made by participants to scale, move, and rotate the terrain. One of the main factors contributing to the relative ease with which participants completed Task 3 was their understanding of how to utilize the pinching gesture to transform the terrain properly.

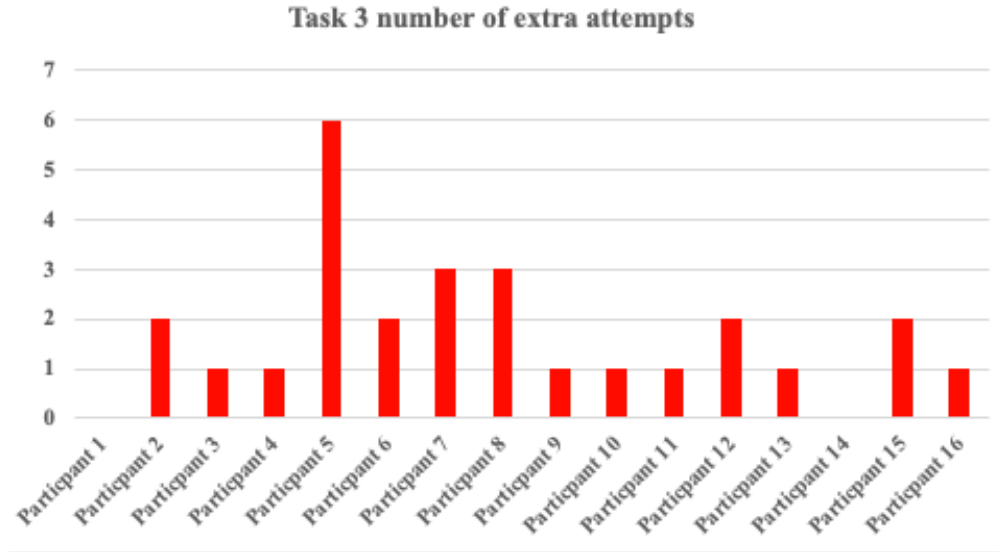


Figure 49. Number of additional attempts to complete task 3.

Table 3. Number of attempts to transform terrain.

	Task 3
Average	1.7
Min	0
Max	6
St. Dev.	1.44

Figures 50, 51, and 52 illustrate the additional attempts taken by participants to assess a position and deploy a military unit. On average, task 4 incurred the highest number of attempts at 4.75, in contrast to Tasks 5 and 6. The primary reason for this discrepancy can be attributed to gaze-tracking and the pinching gesture, and a small box collider on each position. The small box collider resulted in participants selecting the position numerous times to activate the range rings and place a unit. To execute this task, the user had first to identify a position and then perform the pinching gesture to display the range rings. Then, if the position was deemed suitable, the user had to repeat the pinching gesture to deploy a military unit. Moreover, in Task 4, the user was required to deploy three infantry units and evaluate six distinct battle positions which resulted in increased time and attempts. In contrast, in tasks 5 and 6, the user had to deploy only one unit and evaluate

three positions. The number of attempts taken to complete Tasks 4–6 is presented in Tables 4, 5, and 6.

Table 4. Number of attempts to evaluate battle positions and place an infantry unit.

	Task 4
Average	4.75
Min	0
Max	9
St. Dev.	2.43

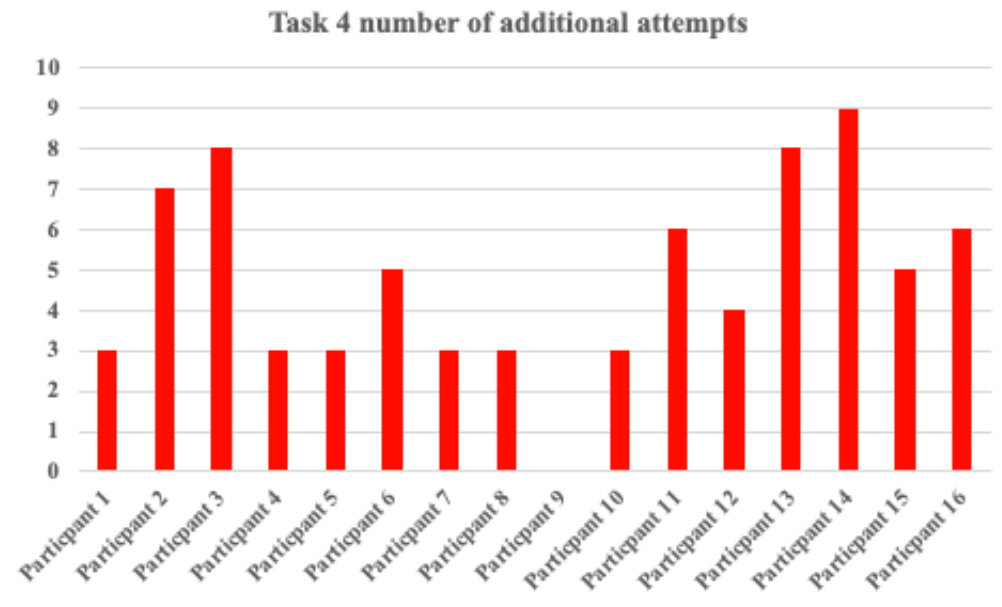


Figure 50. Number of additional attempts to complete task 4.

Table 5. Number of attempts to evaluate PAA and place an artillery unit.

	Task 5
Average	2.18
Min	0
Max	4
St. Dev.	1.47

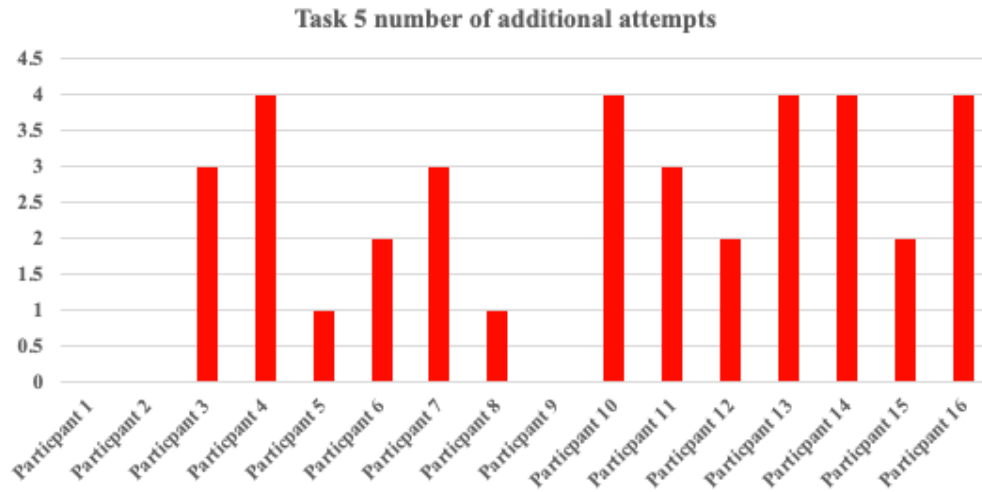


Figure 51. Number of additional attempts to complete task 5.

Table 6. Number of attempts to evaluate a crossing site and place an engineer unit.

	Task 5
Average	1.65
Min	0
Max	4
St. Dev.	1.25

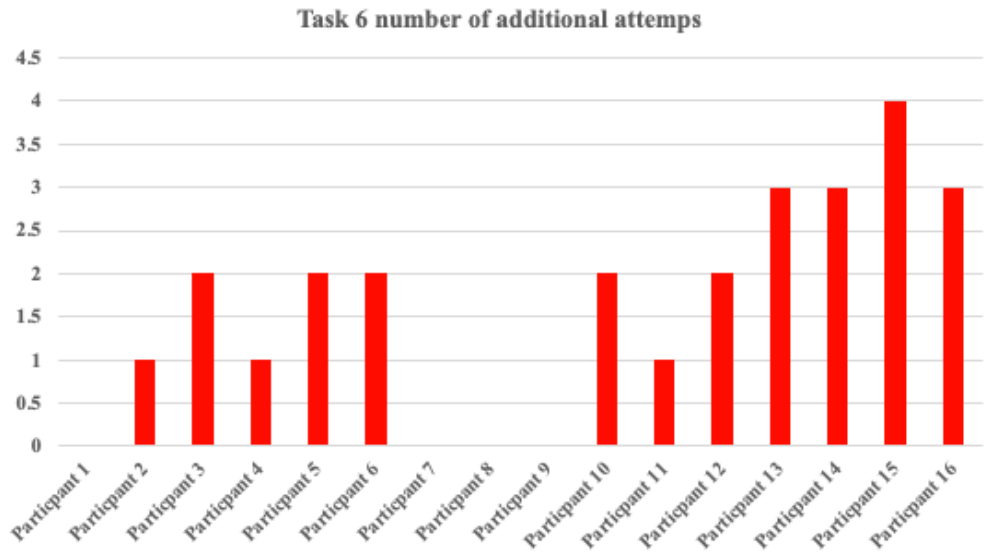


Figure 52. Number of additional attempts to complete task 6.

Task 7, which involved evaluating enemy positions, had the lowest attempts to complete out of Tasks 4–7; the number of attempts it took for a participant to finish this task is presented in Figure 53. Additionally, Table 7 shows the average distribution of participants’ attempts to complete the task. There are two primary reasons why participants completed this task with fewer errors. Firstly, the enemy position was already pre-positioned on the terrain, eliminating the need for the user to place the enemy unit. Therefore, all the users had to do was select the enemy position and evaluate the range rings. Secondly, the user was already familiar with the task, which was identical to the process used in Tasks 4 to 6. As a result, the user became acquainted with the system, contributing to their improved performance.

Table 7. Number of attempts to evaluate enemy positions.

	Task 7
Average	1.25
Min	0
Max	5
St. Dev.	1.34

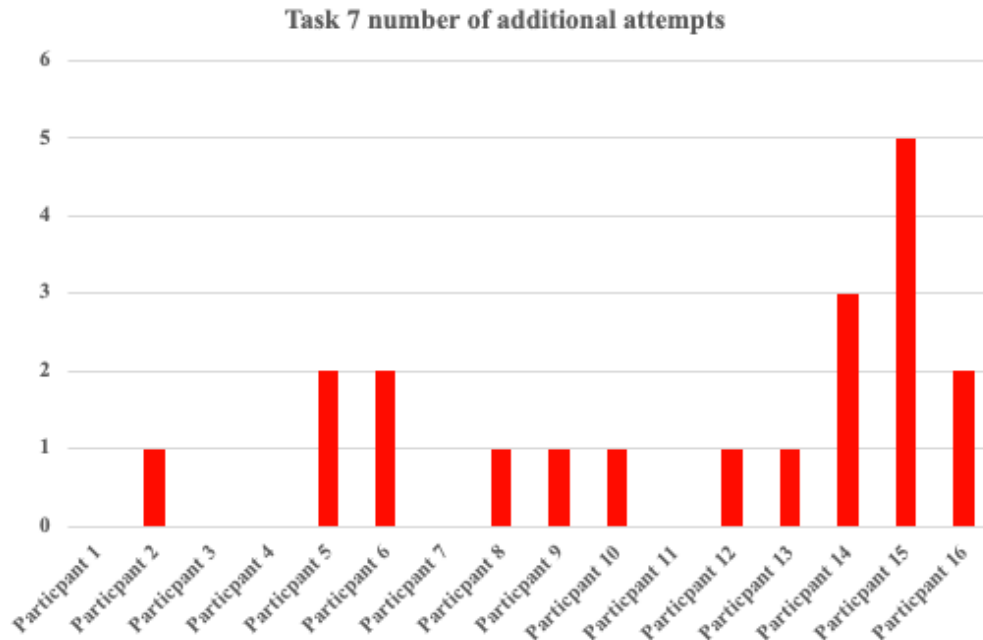


Figure 53. Number of additional attempts to complete task 7.

The last task the user is asked to complete is the WGC scenario. When task 8 is activated, the user has the functionality of all tasks that were completed. For Task 8 the average attempts it took a user to complete the task was 2.75. Figure 54 shows the number of additional attempts a user had to conduct to complete the task. Table 8 shows the number of attempts it took the user to place three infantry units and one artillery and engineer unit.

Table 8. Number of attempts to evaluate a wet gap crossing.

	Task 8
Average	2.75
Min	0
Max	9
St. Dev.	2.23

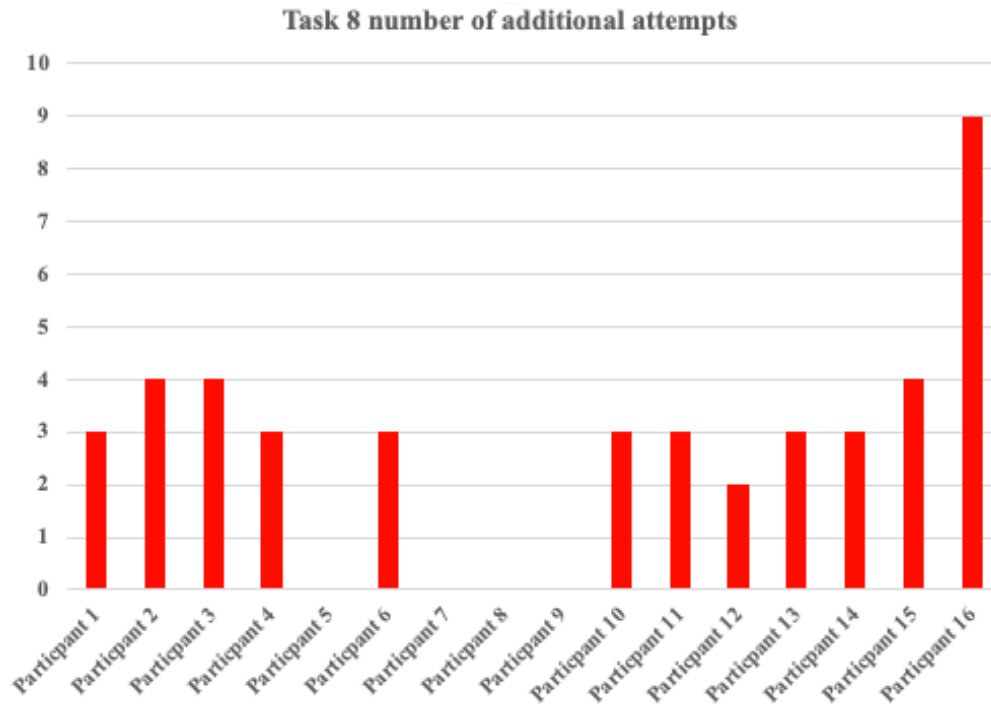


Figure 54. Number of attempts to complete task 8.

2. Subjective Data Set

a. Simulator Sickness Questionnaire (SSQ)

Before the experiment, participants were administered an SSQ questionnaire at two points: after the initial H-Tips training session (SSQ1) and after the main session (SSQ2). I used the scoring criteria developed by Kennedy et al. to transcribe and score the participants' responses. The SSQ includes 16 questions assessing specific symptoms, divided into three main categories: nausea, oculomotor, and disorientation. Participants rated each symptom on a scale of zero to three, with zero indicating no signs, one indicating slight, two indicating moderate, and three exhibiting severe symptoms (Kennedy et al., 1993).

By Kennedy et al.'s evaluation standards, a score of 0 implies the absence of any symptoms, a score of <5 indicates negligible symptoms, a score of 5–10 suggests minimal symptoms, a score of 10–15 indicates significant symptoms, a score of 15–20 implies that the symptoms are a cause for concern, and a score greater than 20 indicates a significant

issue with the simulation (Kennedy et al., 1993). The study’s findings showed an average score of 5.33 among all participants, suggesting that the participants may experience slight symptoms (Table 9).

Table 9. SSQ overall scores

	SSQ
Nausea	0.60
Oculomotor	4.73
Disorientation	0.00
Total Score	5.33

To establish a baseline for each symptom, I assessed participants’ symptoms after completing the H-Tips training (see Figure 55). The results show out of the 16 participants, three experienced slight symptoms from conducting the H-Tips training. The first participant reported a “slight discomfort” from wearing the HL2, and two other participants reported “slight fatigue” from holding their arm out in front of their body while conducting the training. However, no participant experienced any symptom at a moderate or severe level.

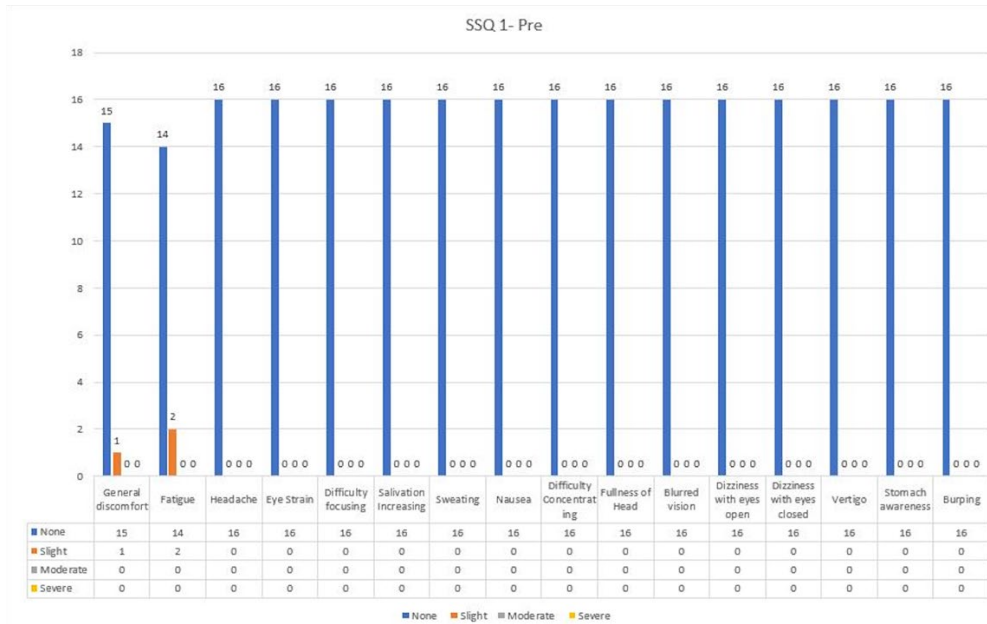


Figure 55. After training session SSQ-1 values

After completing the eight tasks in the WGC scenario, all participants were instructed to fill out the post-task SSQ-2. Based on the data collected from SSQ-2 (refer to Figure 56), it was found that one participant experienced slight discomfort, one participant suffered from slight fatigue, and two participants reported “slight headache” and “eye strain” due to using the HL2. The reason behind the headache and eye strain was that the prototype relied on gaze-tracking to complete tasks, which required the participants to focus and maintain a steady gaze. Those who reported these symptoms specified that they were at a slight level, and no participants reported experiencing them at a moderate or severe level.

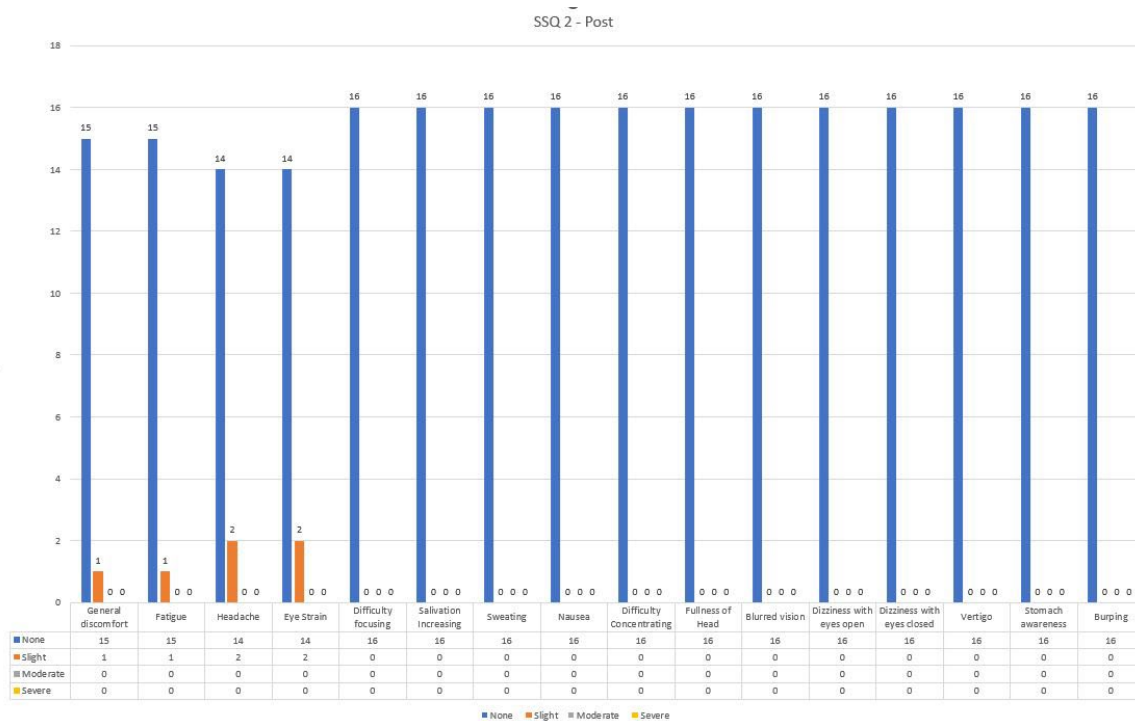


Figure 56. After training session SSQ-2 values

Most participants had no significant symptom change between SSQ-1 and SSQ-2. However, there was a 12.5% increase among those who reported experiencing slight headaches and eye strain after conducting the experiment.

b. System Usability Scale (SUS) Questionnaire

The System Usability Scale (SUS) enables an assessment of the suitability of a tool within a particular context or its “fitness for purpose,” as well as identifying the difficulties users encounter during their operations (Kennedy et al., 1993). Table 10 displays the frequency of responses from participants for each value. Meanwhile, Table 11 shows the overall rating of the prototype by a user and the system’s overall rating. Figure 57 displays the overall results of the SUS questionnaire. In a journal article by Bangor, Kortum, and Miller, they developed a grade scale based for the SUS based on the following criteria: 90–100 = A (best imaginable), 80–89 = B (excellent), 70–79 = C (good), 60–69 = D, 0–59 = F (Bangor et al., 2009).

Table 10. SUS questionnaire: frequency of participants' responses.

	5 = Strongly agree	4 = Agree	3 = Neutral	2 = Disagree	1 = Strongly disagree
1. I think that I would like to use this system frequently	5	9	2	0	0
2. I found the system unnecessarily complex	0	0	1	8	7
3. I thought the system was easy to use	6	10	0	0	0
4. I think that I would need the support of a technical person to be able to use this system	0	0	1	8	7
5. I found the various functions in this system were well integrated	5	10	1	0	0
6. I thought there was too much inconsistency in this system	0	0	4	5	7
7. I would imagine that most people would learn to use this system very quickly	7	7	2	0	0
8. I found the system very cumbersome to use	0	0	2	6	8
9. I felt very confident using this system	6	8	1	1	0
10. I needed to learn a lot of things before I could get going with this system	5	0	2	5	4

Table 11. SUS questionnaire: participants' response analysis.

Participant	SUS score	Grade
1	57.5	F
2	95	A
3	87.5	B
4	70	C
5	82.5	B
6	82.5	B
7	80	B
8	75	C
9	80	B
10	70	C
11	75	C
12	80	B
13	100	A
14	97.5	A
15	87.5	B
16	95	A
Average	69.07	
Min	57.5	
Max	100	
StdDev	18.31	

The analysis of SUS questionnaires is presented in Tables 10 and 11. The overall evaluation of the system is based on the average SUS score of 69.07 which means the system is valued as “Okay” (shown in Table 11).

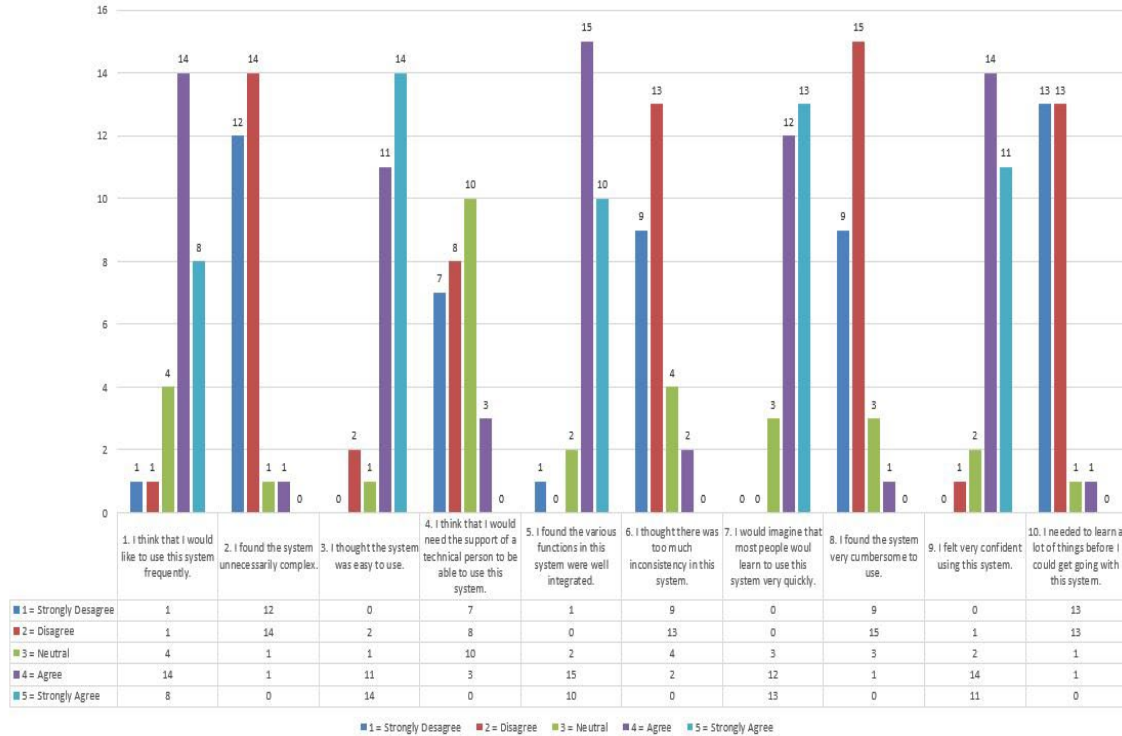


Figure 57. System usability scale.

c. Post-task questionnaire

I gathered feedback from participants using 31 post-task questions that enabled them to reflect on various aspects of the virtual terrain environment system. The questions covered the system’s usefulness, the participant’s performance, and any challenges they encountered while using the prototype. Specifically, questions 1–14 assessed the system’s value in terms of functionality, ease of use, potential multi-user collaboration during MDMP, terrain visualization, and feedback on system design. The remaining questions (15-31) were focused on the participants’ performance during the eight tasks they completed in the experiment, allowing them to rate their performance and suggest any improvements that could be made for each task. Figures 58 and 59 display the ease of use and difficulty rating of the prototype.

The analysis of the data suggests the following:

- Question 1: “How effective would it be to use this type of system during the military planning process?”

- Results: Very ineffective = 0 (0%), Ineffective = 1 (6.25%), Neutral = 1 (6.25%) Effective = 10 (62.5%), Very effective = 4 (25%), Total: 16 participants (100%).
- Question 2: *“How effective was the visualization of the terrain using augmented reality technology?”*
 - Results: Very ineffective = 0 (0 %), Ineffective = 0 (0%), Neutral = 1 (6.25%) Effective = 8 (50%), Very effective = 7 (43.75%), Total: 16 participants (100%).
- Question 3: *“How effective was the overall functionality of the system?”*
 - Results: Very ineffective = 0 (0%), Ineffective = 1 (6.25%), Neutral = 6 (37.50%) Effective = 7 (43.75%), Very effective = 2 (12.5%), Total: 16 participants (100%).
- Question 4: *“How was your overall experience with the user interface of the system?”*
 - Results: Very difficult = 0 (0%), Difficult = 1 (6.25%), Neutral = 3 (18.75 %) Easy = 8 (50%), Very easy = 4 (25%), Total: 16 participants (100%).
- Question 5: *“How effective would this type of system be for two or more users who would collaborate on the same tasks?”*
 - Results: Very ineffective = 0 (0%), Ineffective = 0 (0 %), Neutral = 1 (6.25%) Effective = 7 (43.75 %), Very effective = 8 (50%), Total: 16 participants (100%).
- Question 6: *“How effective would it be to use this type of system to understand unit placement during a military planning process?”*
 - Results: Very ineffective = 0 (0 %), Ineffective = 0 (0 %), Neutral = 1 (6.25%) Effective = 9 (56.25%), Very effective = 6 (37.50%), Total: 16 participants (100%).

- Question 7: *“If there were any issues with the interface, please explain what they were?”*
 - Results: the gaze casting and pinching interface made it difficult to select and be accurate with your selections.
- Question 8: *“If there were any element of the system and its user interface that was done very well, please explain what they were?”*
 - Results: The handles on the terrain manipulation were easy to use.
- Question 9: *“How easy or difficult was it to navigate through the terrain? (i.e., move around and analyze the terrain)”*
 - Results: Very difficult = 0 (0 %), Difficult = 0 (0 %), Neutral = 1 (6.25%) Easy = 11 (68.75%), Very easy = 4 (25.00%), Total: 16 participants (100%).
- Question 10: *“If there were any issues with navigation, please explain what they were?”*
 - Results: The pinching gesture would sometimes default to selecting two different grids.
- Question 11: *“How easy or difficult was it to interact with the menus?”*
 - Results: Very difficult = 0 (0%), Difficult = 1 (6.25%), Neutral = 1 (6.25%) Easy = 9 (56.25%), Very easy = 5 (31.25%), Total: 16 participants (100%).
- Question 12: *“If there were any issues with interacting with the menus, please explain what they were?”*
 - Results: The menus were very far away and required to completely look away from the scene to see the menus.
- Question 13: *“How was your overall experience with the prototype visualization system you used?”*

- Results: Very dissatisfied = 0 (0%), Dissatisfied = 1 (6.25%), Neutral = 2 (12.50%) Satisfied = 9 (56.25%), Very satisfied = 4 (25%), Total: 16 participants (100%).
- Question 14: *“If there were any issues, please explain what they were?”*
Results: the gaze cast and pinch selection did not perform well when trying to navigate.

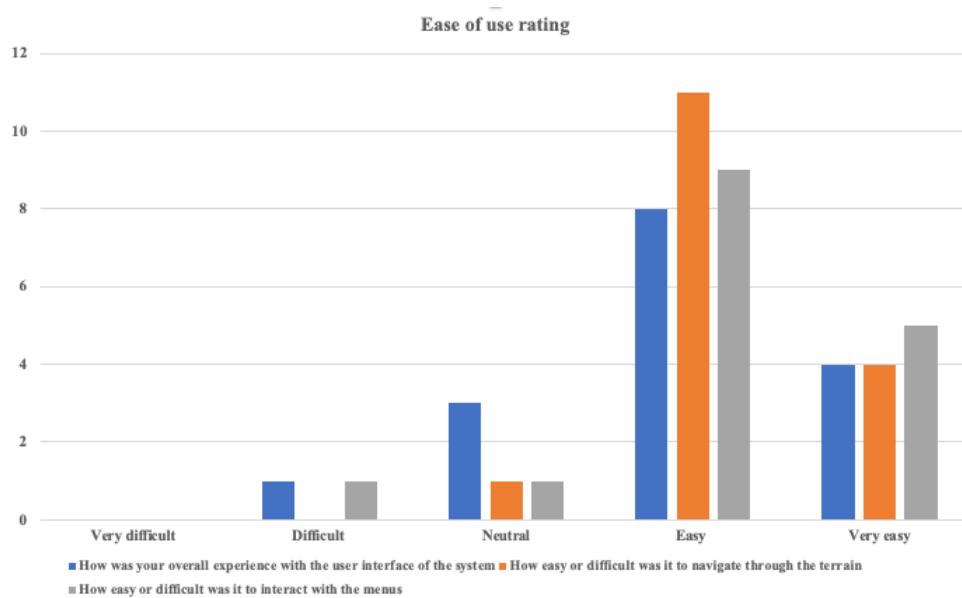


Figure 58. Ease of use rating.

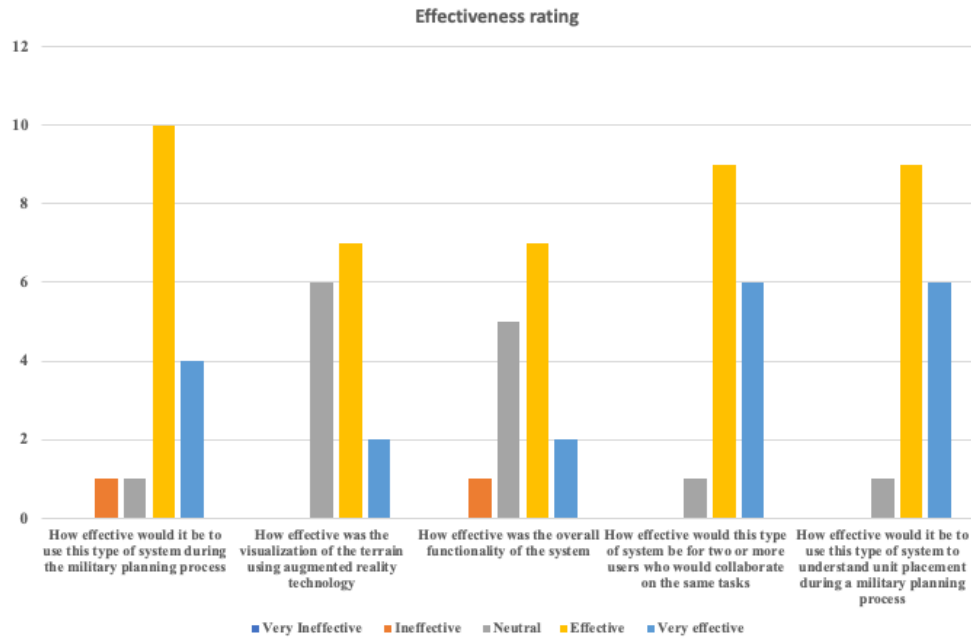


Figure 59. Effectiveness rating.

The answers to questions 15–31 indicate user satisfaction with performing the tasks (Figure 60). The analysis of the data suggests the following:

- Question 15: *“In Task 1 you were asked to find a 6-digit grid. How would you rate your performance?”*
 - Results: Very dissatisfied = 0 (0%), Dissatisfied = 0 (0%), Neutral = 3 (18.75%) Satisfied = 8 (60%), Very satisfied = 5 (31.25%), Total: 16 participants (100%).
- Question 16: *“What improvements would you want to see regarding Task 1 and visualization that supported it?”*
 - Results: the accuracy of gaze casting made finding the 6-digit grid cumbersome.
- Question 17: *“In Task 2 you were asked to find two points on terrain and report their distance. How would you rate your performance?”*

- Results: Very dissatisfied = 0 (0%), Dissatisfied = 0 (0%), Neutral = 3 (18.75%) Satisfied = 6 (37.50%), Very satisfied = 7 (43.75%), Total: 16 participants (100%).
- Question 18: *“What improvements would you want to see regarding Task 2 and visualization that supported it?”*
 - Results: add grid lines.
- Question 19: *“In Task 3 you were asked to rotate the map. How would you rate your performance?”*
 - Results: Very dissatisfied = 0 (0%), Dissatisfied = 0 (0%), Neutral = 1 (6.25%) Satisfied = 9 (56.25%), Very satisfied = 6 (37.50%), Total: 16 participants (100%)
- Question 20: *“What improvements would you want to see regarding Task 3, the visualization and interaction that supported it?”*
 - Results: The toggles could have arrows on them to indicate their function.
- Question 21: *“In Task 4 you were asked to report information on Movement and Maneuver. How would you rate your performance?”*
 - Results: Very dissatisfied = 0 (0%), Dissatisfied = 0 (0%), Neutral = 1 (6.25%) Satisfied = 9 (56.25%), Very satisfied = 6 (37.50%), Total: 16 participants (100%)
- Question 22: *“What improvements would you want to see regarding Task 4, the visualization and interaction that supported it?”*
 - Results: An AI system that could analyze user’s placement and make recommendations to the user.
- Question 23: *“In Task 5 you were asked to report information on Fires. How would you rate your performance?”*

- Results: Extremely dissatisfied = 0 (0%), Dissatisfied = 0 (0%), Neutral = 0 (0%) Satisfied = 9 (56.25%), Extremely satisfied = 7 (43.75%), Total: 16 participants (100%)
- Question 24: *“What improvements would you want to see regarding Task 5, the visualization and interaction that supported it?”*
 - Results: An AI assessment.
- Question 25: *“In Task 6 you were asked to report information on Protection. How would you rate your performance?”*
 - Results: Extremely dissatisfied = 0 (0%), Somewhat dissatisfied = 0 (0%), Neutral = 1 (6.25%) Satisfied = 9 (56.25%), Extremely satisfied = 6 (37.50%), Total: 16 participants (100%).
- Question 26: *“What improvements would you want to see regarding Task 6, the visualization and interaction that supported it?”*
 - Results: An AI assessment.
- Question 27: *“In Task 7 you were asked to report information on an enemy. How would you rate your performance?”*
 - Results: Extremely dissatisfied = 0 (0%), Somewhat dissatisfied = 0 (0%), Neutral = 3 (18.75%) Satisfied = 8 (50%), Extremely satisfied = 5 (31.25%), Total: 16 participants (100%)
- Question 28: *“What improvements would you want to see regarding Task 7, the visualization and interaction that supported it?”*
 - Results: the battle position was difficult to interact with.
- Question 29: *“In Task 8 you were asked to plan a wet gap crossing. How would you rate your performance?”*
 - Results: Extremely dissatisfied = 0 (0%), Somewhat dissatisfied = 0 (0%), Neutral = 2 (12.50%) Satisfied = 10 (62.50%), Extremely satisfied = 4 (25%), Total: 16 participants (100%).

- Question 30: “What improvements would you want to see regarding Task 8, the visualization and interaction that supported it?”
 - Results: AI assessment or in a training mode that could discuss the placement of units and why it was good/bad.
- Question 31: “Any additional comments/remarks”
 - Results: The additional information provided in the information pane is very helpful and has the potential to add significant value to the planning process.

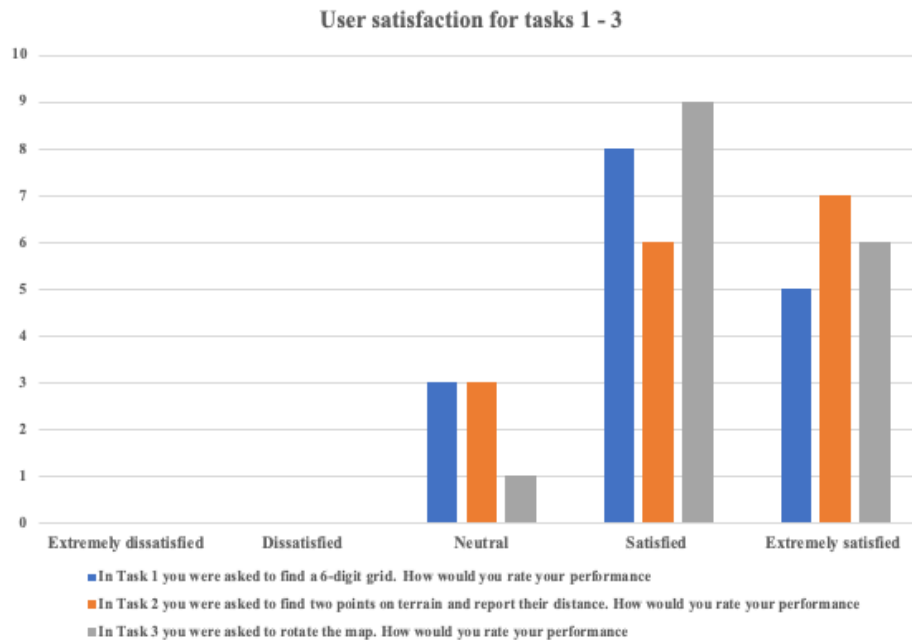


Figure 60. Satisfaction rating for Tasks 1–3.

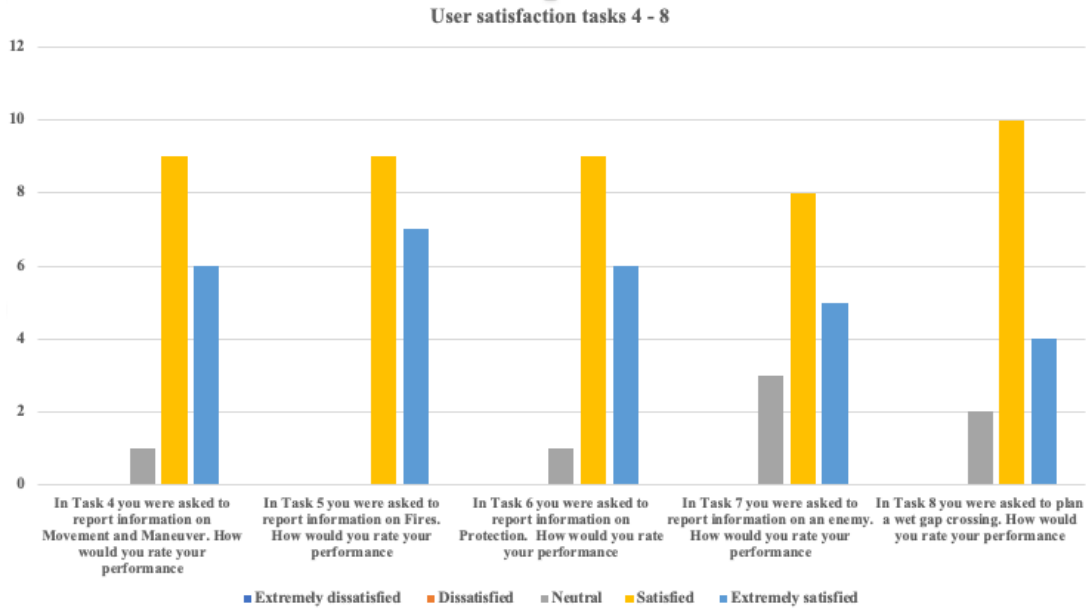


Figure 61. Satisfaction rating for Tasks 4–8.

G. CHAPTER SUMMARY

In this chapter, an overview of the components of a usability study was examined, including the IRB process, study design, study tasks, data collection, and study procedures. In addition, a comprehensive examination of the study participants thoroughly analyzed and discussed the resulting data sets. Finally, I also took note of the participants’ suggestions regarding potential enhancements and extended utilization of virtual terrain environments within the military domain for conducting mission planning.

VI. CONCLUSION AND FUTURE WORK

A. CONCLUSION

In summary, the virtual terrain prototype showcased the potential of leveraging low-cost COTS technologies to create an innovative prototype that enhances staff members' ability to visualize and engage with virtual terrain. Additionally, following the user study, most participants believed that an AR HMD would greatly benefit military personnel when analyzing terrain during mission planning sessions.

The user study involved the participation of 16 participants from various branches of service and NPS faculty members, and it spanned almost 25 hours to experiment. It yielded hundreds of subjective and objective data points, providing valuable insights into the advantages and challenges of using AR for displaying and interacting with virtual terrain.

Chapter V presents conclusive evidence that a low-cost AR solution can be used to view virtual terrain in 3D, facilitating a new way for staff members to view and analyze terrain for mission planning. Moreover, this chapter demonstrates that it is technologically feasible to export real-world terrain into a software game engine and display it in AR for user interaction. This chapter highlights this work's significant contributions to AR, terrain visualization, and visualization research. Furthermore, it recommends areas for future research, prototyping, and similar efforts in the military AR domains. It also suggests directions for future work and proposes ideas for implementing AR to enhance military planning.

B. DOMAIN CONTRIBUTIONS

The study I conducted has contributed to various domains. First, I have presented empirical evidence regarding the potential and value of visualizing virtual terrain using a low-cost, COTS AR device. This technology enables extracting real-world terrain, exporting the landscape to a software engine, and displaying the terrain in AR, allowing users to conduct basic military planning. This answers the first research question, "*What is the technological framework to provide effective support MDMP?*"

Moreover, the data gathered from the experiment answered the fourth research question, “*Can the AR-supported MDMP tool effectively aid military personnel in collaborating during a combined arms scenario?*” Nearly all the study’s participants expressed that the prototype would benefit multiple staff members working together during mission planning.

In the field of AR visualization, the prototype demonstrated a novel way of viewing 3D terrain in contrast to historical analog maps and various mission command systems. This also answered the second and third research questions, “*Can AR support MDMP to enhance the understanding of terrain by providing derivative information and assist with resource management?*” and “*Can the AR-supported MDMP tool effectively assist military staff collaboration in combined arms scenarios?*” The prototype also proved that military members could use a single system to analyze and extract derivative information from the terrain instead of using numerous mission command systems and analog 2D maps simultaneously.

C. FUTURE WORK

While this research successfully evaluated the usability of an AR terrain visualization prototype for staff members to view terrain in 3D and make informed decisions for a commander, future work is necessary to make the prototype more applicable to real-world mission planning.

Additional features and capabilities should be incorporated into the prototype to achieve this. For instance, accurate military symbology objects should be included to enable WFF functions to plan accurately in real-time. In addition, adding grid and phase lines with accurate symbology can further enhance the planning process. Moreover, building and testing models of weapon capabilities with accurate line-of-sight tools can significantly increase the prototype’s usability.

The current prototype is designed solely for planning and evaluating land-based military operations, lacking the essential features for air and sea operations. Consequently, the prototype’s capabilities are limited, given that most large-scale military endeavors entail coordination between various branches of the armed forces. Therefore, to enhance

the system's functionality, it is imperative to collaborate with other service branches to integrate and showcase their operations within the system.

Although the experiment was designed for a single user using HL2, future work can maximize collaboration between staff members by including additional features, such as multiple users using an AR HMD to interact with the virtual terrain. This would enable all WFFs to collaborate in real time and improve the overall effectiveness of the prototype. Therefore, incorporating these additional features in the prototype can enhance its usability and applicability for real-world mission planning.

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APPENDIX A. GRIDCELL

```
using UnityEngine;

namespace SCAMDMPARTS.Grid {
// Data structure for what represents a single cell in the terrain grid
public class GridCell {
public int row;
public int col;
public int xOffset;
public int yOffset;
public Vector3 position;

// -----
public GridCell(int row = -1, int col = -1) {
this.row = row;
this.col = col;
}

// -----
public GridCell(int row, int col, int xOffset, int yOffset, Vector3 position) {
this.row = row;
this.col = col;
this.xOffset = xOffset;
this.yOffset = yOffset;
this.position = position;
}

// -----
public bool IsCell(GridCell other) {
if (other == null) {
return false;
}
return this.row == other.row && this.col == other.col;
}

// -----
public bool IsCell(int row, int col) {
return this.row == row && this.col == col;
}

// -----
public string ToString(int startingRowNumber, int startingColNumber, int padding) {
return $"AB {PadNumber(this.row + startingRowNumber, padding)}{xOffset} {PadNumber(this.col +
startingColNumber, padding)}{yOffset}";
}

// -----
private string PadNumber(int number, int padding) {
return $"{number}".PadLeft(padding, '0');
}
}
}
```

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APPENDIX B. GRIDINTERACT

```
using System;
using UnityEngine;
using Microsoft.MixedReality.Toolkit.Input;
using Shared.EventLog;
using SCAMDMPARTS.Util;

namespace SCAMDMPARTS.Grid {
// Class in charge of interacting with a grid a terrain has split into
[RequireComponent(typeof(Collider))]
public class GridInteractable : MonoBehaviour, IMixedRealityPointerHandler {
public delegate void GridCellEvent(GridCell cell, Vector3 position);
public event GridCellEvent OnStartChange;
public event GridCellEvent OnEndChange;

[Tooltip("Log to write events to")]
public EventLog eventLog;
[Tooltip("Scriptable variable to set the terrain bounds on")]
public BoundsScriptableVariable terrainBounds;
[Tooltip("Number of rows/columns in the grid")]
public int gridSize = 10;
[Tooltip("Number to start with when labeling row cells")]
public int rowStartingNumber = 10;
[Tooltip("Number to start with when labeling column cells")]
public int colStartingNumber = 10;
[Tooltip("Time in seconds to delay before registering pointer events as multi-select")]
public float dragDelay = 0.125f;

private Vector3 _originalScale;
private GridCell _startCell;
private DateTime _pointerStart;

// -----
private void Awake() {
_originalScale = transform.lossyScale;
terrainBounds.Value = GetComponent<Collider>().bounds;
}

// -----
private void OnDisable() {
Reset();
}

// -----
public void Reset() {
OnStartChange?.Invoke(null, Vector3.zero);
OnEndChange?.Invoke(null, Vector3.zero);
}

// -----
public void OnPointerClicked(MixedRealityPointerEventData eventData) {}

// -----
public void OnPointerDown(MixedRealityPointerEventData eventData) {
var worldPosition = eventData.Pointer.Result.Details.Point;
var localPosition = eventData.Pointer.Result.Details.PointLocalSpace;
_startCell = GetGridCell(localPosition, worldPosition.y);
}
```

```

OnStartChange?.Invoke(_startCell, worldPosition);
OnEndChange?.Invoke(_startCell, worldPosition);
eventLog.Add("Grid Cell Selected," _startCell.ToString(rowStartingNumber, colStartingNumber,
GetMaxCoordinateLength()));
_pointerStart = DateTime.Now;
}

// -----
public void OnPointerDragged(MixedRealityPointerEventData eventData) {
if (HasPassedPointerDelay()) {
var worldPosition = eventData.Pointer.Result.Details.Point;
var localPosition = eventData.Pointer.Result.Details.PointLocalSpace;
OnEndChange?.Invoke(GetGridCell(localPosition, worldPosition.y), worldPosition);
}
}

// -----
public void OnPointerUp(MixedRealityPointerEventData eventData) {
if (HasPassedPointerDelay()) {
var worldPosition = eventData.Pointer.Result.Details.Point;
var localPosition = eventData.Pointer.Result.Details.PointLocalSpace;
var selectedCell = GetGridCell(localPosition, worldPosition.y);
OnEndChange?.Invoke(selectedCell, worldPosition);
if (!_startCell.IsCell(selectedCell)) {
eventLog.Add("Second Grid Cell Selected," selectedCell.ToString(rowStartingNumber, colStartingNumber,
GetMaxCoordinateLength()));
}
}
}

// -----
public int GetMaxCoordinateLength() {
var maxNumber = Mathf.Max(rowStartingNumber + gridSize, colStartingNumber + gridSize);
if (maxNumber > 0) {
var digitCount = 0;
while (maxNumber > 0) {
maxNumber /= 10;
++digitCount;
}
return digitCount;
}
return 1;
}

// -----
private bool HasPassedPointerDelay() {
return (DateTime.Now - _pointerStart).TotalSeconds > dragDelay;
}

// -----
private GridCell GetGridCell(Vector3 position, float worldHeight) {
// MRTK's local position seems to be based on the original bounds size at startup,
// So we have to invert this original scale to get it in the current local space to
// calculate which grid cells this position is in
var boundsSize = InvertScale(terrainBounds.Value.size, _originalScale);
position += boundsSize * 0.5f;
var gridX = position.x / boundsSize.x * (float)gridSize;
var gridY = position.z / boundsSize.z * (float)gridSize;
var gridRow = Mathf.FloorToInt(gridX);
var gridCol = Mathf.FloorToInt(gridY);
}

```

```

var offsetX = Mathf.FloorToInt((gridX - gridRow) * 10.0f);
var offsetY = Mathf.FloorToInt((gridY - gridCol) * 10.0f);

// The actual cell world position, however, uses the actual current transform and bounds data
// So calculate it accordingly
var scaleDelta = InvertScale(transform.lossyScale, _originalScale);
var corner = transform.position - transform.rotation * Vector3.Scale(terrainBounds.Value.size, scaleDelta) *
0.5f;
var sectionSize = terrainBounds.Value.size / (float)gridSize;
var cellPosition = corner + Vector3.Scale(transform.right * sectionSize.x, scaleDelta) * (gridRow + 0.5f) +
Vector3.Scale(transform.forward * sectionSize.z, scaleDelta) * (gridCol + 0.5f);
cellPosition.y = worldHeight;
Debug.Log($"Grid cell at {cellPosition} = ({gridRow + rowStartingNumber}, {gridCol + colStartingNumber})");
return new GridCell(gridRow, gridCol, offsetX, offsetY, cellPosition);
}

// -----
private Vector3 InvertScale(Vector3 input, Vector3 scale) {
return new Vector3(input.x / scale.x, input.y / scale.y, input.z / scale.z);
}
}
}
}

```

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APPENDIX C. GRIDLABELS

```
using UnityEngine;

namespace SCAMDMPARTS.Grid {
// Class in charge of adding labels to a terrain grid
[RequireComponent(typeof(GridInteractable))]
public class GridLabels : MonoBehaviour {
public float padding = 0.1f;
public float height = 1.0f;
public GridLabel labelPrefab;
public Transform labelRoot;

// -----
private void Awake() {
var gridInteractable = GetComponent<GridInteractable>();
var bounds = GetComponent<Collider>().bounds;

var sectionSize = bounds.size / (float)gridInteractable.gridSize;
var bottomLeftCorner = bounds.center - transform.rotation * bounds.size * 0.5f;
bottomLeftCorner.y = bounds.center.y;
var boundsWidth = (transform.rotation * bounds.size).x;
var boundsLength = (transform.rotation * bounds.size).z;

// Create row labels
var rowStartingPosition = bottomLeftCorner + transform.right * sectionSize.x * 0.5f;
CreateLabels(rowStartingPosition - transform.forward * padding, transform.right, sectionSize.x,
gridInteractable.gridSize, gridInteractable.rowStartingNumber);
CreateLabels(rowStartingPosition + transform.forward * padding + transform.forward * boundsLength,
transform.right, sectionSize.x, gridInteractable.gridSize, gridInteractable.rowStartingNumber);

// Create column labels
var colStartingPosition = bottomLeftCorner + transform.forward * sectionSize.x * 0.5f;
CreateLabels(colStartingPosition - transform.right * padding, transform.forward, sectionSize.x,
gridInteractable.gridSize, gridInteractable.colStartingNumber);
CreateLabels(colStartingPosition + transform.right * padding + transform.right * boundsWidth,
transform.forward, sectionSize.x, gridInteractable.gridSize, gridInteractable.colStartingNumber);
}

// -----
private void CreateLabels(Vector3 startingPosition, Vector3 direction, float itemSize, int itemCount, int
startingNumber) {
for (var index = 0; index < itemCount; ++index) {
if (index % 5 == 0) {
var endPosition = startingPosition + Vector3.up * height * transform.lossyScale.y;
var label = Instantiate(labelPrefab, endPosition, Quaternion.identity, labelRoot);
label.SetLabel(new Vector3[]{ Vector3.down * padding * 2.0f, Vector3.down * (height + padding * 2.0f) },
$" {index + startingNumber}");
}
startingPosition += direction * itemSize;
}
}
}
}
```

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APPENDIX D. RECRUITMENT FLYER

Experience Visualization of Mission Planning with Augmented Reality (AR)



You are invited to help fellow students' thesis research and participate in a Naval Postgraduate School research study entitled "Supporting Combined Arms Military Decision-Making Process with AR Technology," which will examine the use of augmented reality to analyze terrain and make decisions in a contested river crossing scenario.

- WHAT:** You will be asked to make operational decisions given a contested river crossing scenario using augmented reality headset.
- WHY:** Study human interaction with virtual terrain in augmented reality
- WHO:** Service members with any background in military planning
- WHEN:** 17-28 April 2023
- WHERE:** Watkins Hall, Room 212B
- LENGTH:** About 60 min
- SCHEDULE:** Email Carl Caroffino
- CONTACTS:** Student 1: Carl Caroffino carl.caroffino@nps.edu
Principal investigator: Dr. Amela Sadagic asadagic@nps.edu
IRB Chair: Dr. Larry Shattuck lgshattu@nps.edu

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APPENDIX E. SIMULATOR SICKNESS QUESTIONNAIRE

No _____

Date _____

SIMULATOR SICKNESS QUESTIONNAIRE

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

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

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

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version : March 2013

***Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3(3), 203-220.

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APPENDIX F. SYSTEM USABILITY SCALE

Subject ID: _____
Date: _____

SUS Questionnaire

**Please reflect and answer the following question based on your experience with the system in this study.*

1. I think that I would like to use this system frequently:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

2. I found the system unnecessarily complex:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

3. I thought the system was easy to use:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

4. I think that I would need the support of a technical person to be able to use this system:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

5. I found the various functions in this system were well integrated:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

6. I thought there was too much inconsistency in this system:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

7. I would imagine that most people would learn to use this system very quickly:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

8. I found the system very cumbersome to use:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

9. I felt very confident using the system:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

10. I needed to learn a lot of things before I could get going with this system:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
-------------------	----------	---------	-------	----------------

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APPENDIX G. DEMOGRAPHICS

Q1 Year of Birth: _____

Q2 Years of Service: _____

Q3 Current Rank: _____

Q4 Branch of Service:

- Army (1)
- Marine Corp (2)
- Air Force (3)
- Navy (4)
- Space Force (5)

Q5 Gender:

- Male (1)
- Female (2)
- Prefer not to say (3)

Q6 Are you colorblind:

- Yes (1)
- No (2)

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APPENDIX H. POST-TASK QUESTIONNAIRE

Post task questionnaire

Q1 How effective would it be to use this type of system during the military planning process?

- Very ineffective (1)
 - Ineffective (2)
 - Neutral (3)
 - Effective (4)
 - Very effective (5)
-

Q2 How effective was the visualization of the terrain using augmented reality technology?

- Very ineffective (1)
 - Ineffective (2)
 - Neutral (3)
 - Effective (4)
 - Very effective (5)
-

Q3 How effective was the overall functionality of the system?

- Very ineffective (1)
 - Ineffective (2)
 - Neutral (3)
 - Effective (4)
 - Very effective (5)
-

Q4 How was your overall experience with the user interface of the system?

- Very difficult (1)
 - Difficult (2)
 - Neutral (3)
 - Easy (4)
 - Very easy (5)
-

Q5 How effective would this type of system be for two or more users who would collaborate on the same tasks?

- Very ineffective (1)
 - Ineffective (2)
 - Neutral (3)
 - Effective (4)
 - Very effective (5)
-

Q6 How effective would it be to use this type of system to understand unit placement during a military planning process better?

- Very ineffective (1)
 - Ineffective (2)
 - Neutral (3)
 - Effective (4)
 - Very effective (5)
-

Q7 If there were any *issues* with the interface, please explain what they were?

- a. _____
 - b. _____
 - c. _____
-

Q8 If there were any element of the system and its user interface that was *done very well*, please explain what they were?

- a. _____
- b. _____
- c. _____

Q9 How easy or difficult was it to navigate through the terrain? (i.e. move around and analyze the terrain)

- Very difficult (1)
- Difficult (2)
- Neutral (3)
- Easy (4)
- Very easy (5)

Q10 If there were any issues with navigation, please explain what they were?

- a. _____
- b. _____
- c. _____

Q11 How easy or difficult was it to interact with the menus?

- Very difficult (1)
- Difficult (2)
- Neutral (3)
- Easy (4)
- Very easy (5)

Q12 If there were any issues with interacting with the menus, please explain what they were?

- a. _____
 - b. _____
 - c. _____
-

Q13 How was your overall experience with the prototype visualization system you used?

- Very dissatisfied (1)
 - Dissatisfied (2)
 - Neutral (3)
 - Satisfied (4)
 - Very satisfied (5)
-

Q14 If there were any issues, please explain what they were?

- a. _____
 - b. _____
 - c. _____
-

Q15 In **Task 1** you were asked to find 8-digit grid. How would you rate your performance?

- Very dissatisfied (1)
 - Dissatisfied (2)
 - Neutral (3)
 - Satisfied (4)
 - Very satisfied (5)
-

Q16 What improvements would you want to see regarding **Task 1** and visualization that supported it?

- a. _____
 - b. _____
 - c. _____
-

Q17 In **Task 2** you were asked to find two points on terrain and report their distance. How would you rate your performance?

- Very dissatisfied (1)
 - Dissatisfied (2)
 - Neutral (3)
 - Satisfied (4)
 - Very satisfied (5)
-

Q18 What improvements would you want to see regarding **Task 2** and visualization that supported it?

- a. _____
 - b. _____
 - c. _____
-

Q19 In **Task 3** you were asked to rotate the map. How would you rate your performance?

- Very dissatisfied (1)
 - Dissatisfied (2)
 - Neutral (3)
 - Satisfied (4)
 - Very satisfied (5)
-

Q20 What improvements would you want to see regarding **Task 3**, the visualization and interaction that supported it?

- a. _____
 - b. _____
 - c. _____
-

Q21 In **Task 4** you were asked to report information on Movement and Maneuver. How would you rate your performance?

- Very dissatisfied (1)
 - Dissatisfied (2)
 - Neutral (3)
 - Satisfied (4)
 - Very satisfied (5)
-

Q22 What improvements would you want to see regarding **Task 4**, the visualization and interaction that supported it?

- a. _____
 - b. _____
 - c. _____
-

Q23 In **Task 5** you were asked to report information on Fires. How would you rate your performance?

- Extremely dissatisfied (1)
 - Somewhat dissatisfied (2)
 - Neither satisfied nor dissatisfied (3)
 - Somewhat satisfied (4)
 - Extremely satisfied (5)
-

Q24 What improvements would you want to see regarding **Task 5**, the visualization and interaction that supported it?

- a. _____
 - b. _____
 - c. _____
-

Q25 In **Task 6** you were asked to report information on Protection. How would you rate your performance?

- Extremely dissatisfied (1)
 - Somewhat dissatisfied (2)
 - Neither satisfied nor dissatisfied (3)
 - Somewhat satisfied (4)
 - Extremely satisfied (5)
-

Q26 What improvements would you want to see regarding **Task 6**, the visualization and interaction that supported it?

- a. _____
 - b. _____
 - c. _____
-

Q27 In **Task 7** you were asked to report information on Enemy. How would you rate your performance?

- Extremely dissatisfied (1)
 - Somewhat dissatisfied (2)
 - Neither satisfied nor dissatisfied (3)
 - Somewhat satisfied (4)
 - Extremely satisfied (5)
-

Q28 What improvements would you want to see regarding **Task 7**, the visualization and interaction that supported it?

- a. _____
 - b. _____
 - c. _____
-

Q29 In **Task 8** you were asked to plan a wet gap crossing. How would you rate your performance?

- Extremely dissatisfied (1)
 - Somewhat dissatisfied (2)
 - Neither satisfied nor dissatisfied (3)
 - Somewhat satisfied (4)
 - Extremely satisfied (5)
-

Q30 What improvements would you want to see regarding **Task 8**, the visualization and interaction that supported it?

- a. _____
 - b. _____
 - c. _____
-

Q31 Any additional comments/remarks:

- a. _____
- b. _____
- c. _____

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