NPS-AM-24-218

ACQUISITION RESEARCH PROGRAM SPONSORED REPORT SERIES

An Empirical Analysis to Determine a Common Augmented Reality or Mixed Reality Solution to Improve Training and Operational Capabilities for the Marine Corps Capability

June 2024

Maj Christopher A. Huff, USMC

Thesis Advisors: Victor R. Garza
Jeffrey R. Dunlap, Lecturer
Dr. Mollie R. McGuire

Department of Defense Management

Naval Postgraduate School

The research presented in this report was supported by the Acquisition Research Program of the Department of Defense Management at the Naval Postgraduate School.

To request defense acquisition research, to become a research sponsor, or to print additional copies of reports, please contact the Acquisition Research Program (ARP) via email, arp@nps.edu or at 831-656-3793.

ABSTRACT

I Marine Expeditionary Force sponsored research to identify methods of developing applications for various augmented reality (AR), virtual reality (VR), and mixed reality (XR) use cases. The research sought to identify methods of hand and arm tracking that would assist with the completion of tasks. This thesis provides the background for the growing demand in the Marine Corps for the use of AR/VR/XR systems grounded in Project Tripoli. The method of thesis research identifies various AR/VR/XR systems that assists in better understanding current capabilities in commercially developed systems. Site visits were conducted to various laboratories to learn about the systems and to learn about a new technology under development by the Defense Advanced Research Projects Agency (DARPA). Perceptually enabled task guidance (PTG) is an artificial intelligence solution to providing task guidance to the user to assist with the completion of various tasks. PTG uses computer vision (CV) technology to identify actions taken by the user and provides detailed instructions for the user to complete the task. Instructions are provided to the user through an AR/XR head-mounted device. AR/XR displays overlay data and projects the data in front of the user where it can be referenced in real time without the need to look away at a laptop, publication, or reference material. AR/XR supported by AI can support multiple military use cases across a wide range of military communities.

THIS PAGE INTENTIONALLY LEFT BLANK

ABOUT THE AUTHOR

Major Christopher A. Huff graduated from Texas Tech University in Lubbock, TX, in 2007 with a Bachelor of Business Administration in International Business. After graduation, he interned in the Office of the Secretary of Defense with the Speech Writer's Group for the Honorable Robert Gates. After joining the Marine Corps, he served as an infantry officer in Afghanistan, supporting Operation Enduring Freedom. After returning from Afghanistan, he completed Naval flight training and flew the AH-1Z attack helicopter for the next eight years deploying on multiple unit deployment rotations in the Indo-Pacific theater. In 2020, he transitioned to fly the MV-22B Osprey and immediately deployed to Djibouti supporting both USAFRICOM and USCENTCOM. He has held every department head billet in an operational fleet squadron and completed his studies through the Naval Postgraduate School distance learning program while serving in those department head billets. Major Huff now serves as a strategic analyst for the Commandant of the Marine Corps' Office of Net Assessment. Major Huff enjoys spending time with his wife and three children attending the many sports and dance activities around the country and abroad. In his free time, when Major Huff is not fixing things around the house, he writes, dreams of owning a boat, and has two dogs: a Great Dane and a Golden Retriever

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would first like to thank my wife, Lauren Huff, for supporting me in my life and through three years of research and progress toward the completion of my Master of Science in Program Management. Thank you for your comedic relief, a listening ear, and a patient heart. Her support was vital and encouraged me by providing clarity during moments of uncertainty and doubt.

Victor Garza, Jeffrey Dunlap, and Dr. Mollie McGuire were critical in providing educational guidance during this research. I want to thank Dr. Johnathan Mun for supporting my original research proposal and providing me with the opportunity to continue my research efforts by introducing me to Victor Garza. Brian Wood was a mentor during this process and assisted with countless reviews of this report and navigation through several challenges.

I want to thank Raymond Jones, the Chair of the Department of Defense Management at the Naval Postgraduate School, for supporting the travel required for this project as well as all the support I received from Karey Shaffer, the program manager for the Acquisition Research Program at the Naval Postgraduate School. I could not have done this without you, Karey.

The Defense Innovation Unit (DIU) was a tremendous resource while conducting this research. Tom Jenkins, the Marine Corps Warfighting Laboratory Liaison at DIU, was instrumental in coordinating the contacts needed to construct this research and I cannot thank you enough.

Brian VanVoorst at Raytheon BBN Technologies, James Kukla at Redshred, and Ryan McKendrick at Northrop Grumman introduced me to Perceptually Enabled Task Guidance (PTG). I want to thank each of them as well as Tom Stephens at the Defense Advanced Research Projects Agency (DARPA) for providing the opportunity to gain experience with PTG technology. United States Marine Corps Major Phillip “Donna” Smith at DARPA assisted with providing contacts and interviews with DARPA Program Managers. Thanks to Donna, I was able to meet Matthew Wilding, DARPA Program

Manager for Intrinsic Cognitive Security and learn about the level of data encryption and cyber defense when using AR/VR/XR systems.

I want to thank Mark Livingston at the Naval Research Laboratory and Peter Squire at the Office of Naval Research (ONR) for providing insight into past and present research on augmented reality developments within the Navy and Marine Corps.

Thomas Mead with the Army Applications Laboratory assisted with shining some light on developments in the Army regarding augmented reality. Army Lieutenant Colonel Denny Dresch, the Army Soldier Warrior Program Manager, was gracious enough to assist with providing access to the Integrated Visual Augmentation System. Chris Domencic with Microsoft was critical in providing access to Microsoft facilities and the ability to learn more about the Integrated Visual Augmentation System.

Doug Seich provided access to the team at Meta to learn more about commercial development in AR/VR/XR systems. I thank him and his team for helping me understand the incredible work that is going on at Meta's Reality Labs. Truly impressive.

Finally, I would like to thank my commander, Lieutenant Colonel Ryan Stevens, for his patience and support while I completed this project.

NPS-AM-24-218

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

An Empirical Analysis to Determine a Common Augmented Reality or Mixed Reality Solution to Improve Training and Operational Capabilities for the Marine Corps Capability

June 2024

Maj Christopher A. Huff, USMC

Thesis Advisors: Victor R. Garza
Jeffrey R. Dunlap, Lecturer
Dr. Mollie R. McGuire

Department of Defense Management

Naval Postgraduate School

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

3D	3 dimensional
ADVTE	Aviation distributed virtual training environment
AI	Artificial intelligence
AITT	Augmented immersive team trainer
AoA	Analysis of Alternatives
AR	Augmented reality
ASALT	The Advanced Small Arms Lethality Trainer
ATAK	Android Tactical Assault Kit
BARS	Battlefield augmented reality system
BI	Business intelligence
C2	Command and control
CAD	Computer aided design
CAS	Close air support
CDD	Capabilities Development Document
CENSECFOR	Center for Security Forces
CFF	Call for fire
CFT	Cross functional team
CIGI	Common image generator interface
CJCSI	Chairman of the Joint Chiefs of Staff Instruction
CNA	Center for Naval Analysis
CNN	Convolutional neural network
COC	Command operations center
CPU	Central Processing Unit
CQB	Close quarters battle
CV	Computer vision
DARPA	Defense Advanced Research Projects Agency
DevSecOps	Development, security, operations

DIS	Distributed interactive simulation
DIU	Defense Innovation Unit
DoDI	Department of Defense Instruction
DOTMLPF-P	Doctrine, Organization, Training, Material, Leadership and Education, Personnel, Facilities, and Policy
EMSO	electromagnetic spectrum operations
EWGIR	Electromagnetic Warfare Ground Instrumented Range
FiST	Fire support team
FMF	Fleet Marine Force
FO	Forward observer
FoFTS	Force-on-Force Next Training System
FOM	Federation object model
FY	Fiscal year
GCE	Ground Combat Element
GPS	Global positioning system
GPU	Graphics Processing Unit
GVTS	Ground vehicle training system
HD	High definition
HLA	High level architecture
HMD	Head-mounted display
HST	Helicopter support team
IBR	Initial Baseline Review
ICD	Initial Capabilities Document
IDV	Indefinite delivery vehicle
IEEE	Institute of Electrical and Electronics Engineers
IETM	Interactive Electronic Technical Manual
ISMT	Indoor Simulated Marksmanship Trainer
IVAS	Integrated visual augmentation system
JFO	Joint fires observer
JLVC	Joint live, virtual, and constructive

JTAC	Joint terminal attack controller
JVT	Joint terminal attack controller virtual trainer
LAN	Local area network
LCE	Logistics Combat Element
LiDAR	Light detection and ranging
LLM	Large language model
LVC	Live, virtual, and constructive
LVC-IA	Live, virtual, and constructive-integrating architecture
LVC-TE	Live, virtual, and constructive training environment
MACE	Modern air combat environment
MAGTF	Marine Air-Ground Task Force
MANET	Mobile ad hoc network
MATV	Mine-resistant, ambush protected vehicle
MCS	Marine Constructive Simulation
MCTE	Marine Corps Training Environment
MCTIS	Marine Corps Tactical Instrumentation Systems
MCTN	Marine Corps Training Network
MDD	Material Development Document
MEF	Marine Expeditionary Force
MET	Mission Essential Task
MIT	Massachusetts Institute of Technology
MTA	Middle tier of acquisition
MTWS	Marine Air-Ground Task Force tactical warfare simulation
MVP	Minimum viable product
NALCOMIS OOMA	Naval Aviation Logistics Command Management Information System for Organizational Maintenance Activities
NAMS	Naval Aviation Maintenance System
NCTE	Navy Continuous Training Environment
NLT	No later than
NOBLE	Naval Operational Business Logistics Enterprise

NOSS	Naval Operational Supply System
NRL	Naval Research Laboratory
OIMA	Optimized Intermediate Maintenance Activities
ONR	Office of Naval Research
OS	Operating System
OTA	Other transaction authority
OUSD	Office of the Undersecretary of Defense
PEMA	Portable electronic maintenance aide
PEO	Program Executive Office
PTG	Perceptually enabled task guidance
RADAR	Radio detection and ranging
RAI	Responsible artificial intelligence
SAVT	Supporting arms virtual trainer
SCM	Supply chain management
SDK	Software development kit
SESAMS	special effects small arms marking system
SOCOM	Special Operations Command
SUTTS	Small unit tactical training system
TA1	Technical area 1
TA2	Technical area 2
TA3	Technical area 3
TCCC	Tactical combat casualty care
TECOM	Training and Education Command
TEn	Tactical environment
TVCS	Tactical video capture system
T&E	Training and Education
T&R	Training and Readiness
USMC	United States Marine Corps
VBS3	Virtual battlespace 3
VR	Virtual reality

WAN	Wide area network
WAR	Warfighter Augmented Reality
XR	Mixed reality

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

I Marine Expeditionary Force (MEF) submitted a research proposal to the Naval Postgraduate School's Naval Research Program for sponsored research. The research proposal can be found in the Naval Research Program list of topics with the Topic Identification NPS-24-M225 titled, "Virtual Reality and Augmented Reality Applications." The proposal discusses exploring augmented reality (AR), virtual reality (VR) and/or mixed reality (XR) capabilities for use in the Marine Corps and how those capabilities can support conducting tasks during training and operations. I MEF requested research to identify and include ways to detect hand/arm motions during tasks while wearing AR/VR/XR systems. I MEF also seeks to understand ways to develop applications that support varying military use cases such as tactical combat casualty care (TCCC), helicopter support teams (HST), or conducting beach landing operations. The research in this thesis seeks to identify an AR/VR/XR system or systems capable of supporting a broad range of mission use cases with the capability to recognize hand/arm motions, identify how applications can be developed for that system or systems, and identify technology under development to assist with the identification of hand and arm motions that would support the various use case system applications.

The identification of hand location and the ability to determine the location of the hands assists in determining what actions are occurring to complete a task such as vehicle maintenance. Displays can overlay data that the user references in real time without the need to look away at a computer screen or map. The system could detect actions that are taken by the user and provide instructions and/or collect data that catalogues the user's actions. Artificial intelligence (AI) can assist the user by providing automated functions, detecting the actions being taken, providing selection options, and providing instructions for the performance of different tasks. Each use case can be defined in a unique application that supports that specific use case. An example of an application could include maintenance support for an MV-22B, or a mine-resistant ambush protected vehicle (MATV). AR/VR/XR systems, supported by AI, can support other mission use cases across the Marine Corps.

The research supporting this thesis looks at systems that are commercially available such as the HoloLens 2 and its military replacement, the Integrated Visual Augmentation System (IVAS) under development by Microsoft and the Army, to determine methods of hand and arm tracking as well as the use of the systems for the development of future applications that support various use cases. AI capabilities for detecting actions, including hand and arm movements, are explored through research undertaken by the Defense Advanced Research Projects Agency (DARPA). DARPA is exploring a concept called Perceptually Enabled Task Guidance (PTG) that uses computer vision to detect actions taken by the user and supports the user with varying methods of instruction during the conduct of task completion.

Research Question:

1. How can augmented reality, virtual reality, or mixed reality be used across a wide range of mission use cases within the Marine Corps?

Supporting Research Questions:

1. How can AR/VR/XR headsets, using AI, be used to support mission use case functions?
2. How can training and operational use of the AR/XR headset be conducted?
3. How can AI support use case functions?

The identification and definition of AR, VR, or XR have been discussed thoroughly in varying professional and academic publications. This study does not attempt to redefine or expand on those definitions. Research conducted for this study supports the use of VR for training and the use of AR or XR for training and operations. The advent and rapid development of XR provides opportunities for improved communication mediums in learning environments and would be beneficial in the conduct of operational command and control. Computer vision can assist with identifying hand and arm positions while conducting varying tasks and identifying the task. The systems reviewed in this thesis support computer vision technology and applications can be developed for various tactical tasks. This study reviews emerging technologies for the creation of applications for use with AR/VR/XR systems that support varying military use case functions across the Marine Corps.

PTG advances the ability to use AR/XR platforms not only in training, but also in operational environments. As the Marine Corps moves to conducting more distributed operations where fewer Marines are expected to perform more tasks, digital task guidance can assist in expanding the skills needed for Marines to perform a wider range of tasks.

The research in this thesis identified AR/VR/XR systems developed commercially and through military research laboratories that contain the necessary technology for the integration of PTG. As PTG technology matures, a greater number of applications will support more tasks for military use.

CV provides methods for identifying actions and assisting in a variety of ways. CV has its limitations and as PTG continues to improve, methods of mitigating those limitations will follow. The Marine Corps would benefit from investing in PTG technology as it aligns with Marine Corps Force Design concepts and is a natural fit in the Project Tripoli portfolio.

THIS PAGE INTENTIONALLY LEFT BLANK

INTRODUCTION

The United States Marine Corps (USMC) continues to explore the benefits of augmented reality (AR), virtual reality (VR), and mixed reality (XR) technologies to improve effectiveness of Marines and sailors in performing tasks. Over the last four decades, each branch of the DOD has focused on VR for use in military training. The advent of video games supported the idea of an immersive experience and increased the demand for VR hardware and software applications. VR headsets have seen tremendous growth throughout the first two decades of the 21st century and have been used extensively in the military to provide more opportunities for training. AR technologies are also not new. AR technology has seen several iterations of growth and development since the last decade of the 20th century and has seen exponential improvements in technological advancement.

A barrier to AR development has notably been the lack of processing power of central processing units (CPU) and the quality of graphics processing units (GPU). As CPU and GPU technology, among others, continues to advance, AR capabilities improve. AR development has historically relied on applications that:

> are built using general purpose processors as development platforms where the processing tasks are executed in software. However, software execution is not always the best solution for the highly intensive requirements of the many processing tasks involved in AR, and it inevitably constrains frame rate and latency, which compromises real time operations, and magnifies size and power consumption, hindering mobility. (Toledo et al., 2010)

Until recently, data processing, latency, and power consumption were sub-optimal for the use of AR to support live and constructive tasks within various environments such as for military or medical application. The advent of advanced microchips and CPUs are enabling data processing at the speed of real-life occurrence. Data collection has rapidly expanded in the last decade and supports a robust repository that can be referenced for the creation of digital imagery overlays or, in the case of XR, 3-dimensional (3D) graphic models that appear immersive within the surroundings of the user. Hardware is improving in ways that support processing copious amounts of data for the presentation of information in new ways. AR and XR capabilities provide novel applications that are useful in military, medical, educational, and other professional vocations. Within the military, the ability for AR and XR systems to support a variety of mission use cases is growing due to technological maturation.

A. INCREASED DEMAND IN THE MARINE CORPS FOR AR/VR/XR

The Marine Corps continues to explore advancements in AR/VR/XR systems with an emphasis on live, virtual, and constructive (LVC) simulation.

1. Live, Virtual, and Constructive-Training

The Live, Virtual, and Constructive-Training Environment (LVC-TE) is a concept broken down into three parts (Training and Education Command [TECOM], 2014a). The live training environment is described as training actions that take place in a natural environment where actions that take place are conducted with real assets, weapons, and people. An example would include shooting rifles on a rifle range with live ammunition. The virtual environment is found via immersive, computer-based simulation. The virtual environment may be provided with a headset that provides virtual reality or can also be achieved with a projection screen that is controlled by the user with a replica of the system hardware components like what is found in an aircraft simulator (TECOM, 2014a). The constructive environment simulates, via computer modeling, the people, environment, and systems operating in that environment (TECOM, 2014a). The constructive environment replicates conditions relative to a geographic location, enemy threat level, operational constraint or restraint and can be imposed on simulated units to generate wargaming analysis (TECOM, 2014a).

This study is not intended to provide a thorough description of LVC-TE. A more thorough review of LVC-TE within the Marine Corps is outlined by Baron Mills in his 2014 joint applied project. Mills discussed the live, virtual, constructive-training environment in a joint applied project with the Naval Postgraduate School titled, *Live, Virtual, and Constructive-Training Environment: A Vision and Strategy for the Marine Corps* (Mills, 2014). In his project, Mills conducts a gap analysis across doctrine, organization, training, material, leadership and education, personnel, facilities, and policy

(DOTMLPF-P) metrics and determines several areas needed to improve the LVC-TE capabilities within the Marine Corps. Mills identifies a "lack of systems designed to support comprehensive mission essential tasks (MET) and/or collective training and readiness (T&R) events" as a gap in the Marine Corps LVC-TE (Mills, 2014, p. 9). Mills alludes to a lack of demand for such systems occurring because the:

> Marine Corps does not have T&R standards that prescribe the use of these capabilities. The Marine Corps has a propensity to let commanders decide for themselves how to achieve their T&R requirements. This means that those commanders and their Marines will not use training systems (and a LVC-TE concept) that they have not been educated on, trained to use, or prescribed to use (Mills, 2014).

The full list of gaps can be found in Mills's joint applied project. Dr. Peter Squire, Program Manager for Human Performance Training and Education at the Office of Naval Research (ONR) states, "Future training systems need to be easily accessible and useable to Marines and complement the type of activities they perform during live-fire exercises" (Duffie, 2021, p. 2).

In 2015, TECOM published the *Concept of Operations for the U.S. Marine Corps Live, Virtual, and Constructive-Training Environment (LVC-TE)* (TECOM, 2014a). The document was the first endorsement by the Marine Corps for the LVC-TE with the approval of the Training and Education Command, Commanding Officer, Major General Lukeman. The Initial Capabilities Document Guidance provided by General James Amos, the Assistant Commandant of the Marine Corps in July 2010, regarding LVC-TE development within the Marine Corps used U.S. Army Live, Virtual, and Constructive-Integrating Architecture (LVC-IA) Initial Capabilities Document as the formative "basis from which the USMC LVC-TE Capabilities were identified for fulfilling DOD training transformation guidance" (TECOM, PowerPoint Slides, 2023). In the Commandant's Planning Guidance, General Joseph Dunford, the Commandant of the Marine Corps in January 2015, stated, "We will prioritize the fielding of capabilities that support MAGTF integration and the development of resilient leaders and sound tactical and ethical decision making at the small unit level. We will continue to support the fielding of systems that enhance our proficiency and safety in operating weapons and equipment" (Dunford, J., 2015, p. 11).

2. Training and Education 2030

The Marine Corps recently released guidance to the force with *Training and Education 2030*. The guidance shapes the direction of the force re-design efforts within training and education occurring across the Marine Corps. The document emphasizes the need for LVC simulation capabilities and explains that "LVC-TE will serve as the cornerstone of how the Marine Corps builds combat readiness during this critical time of transformation" (USMC, 2023, p. 8). The focus for LVC simulation in the document is centered around training, but as systems continue to improve, LVC simulation is available in both training and live combat operations. Improvements in hardware and processing speeds have reduced latency, improved designs, and increased more opportunities for using AR/XR systems in operational environments. An example of what improved LVC-TE capabilities may look like is outlined in the *Training and Education 2030* document and is highlighted below.

> Picture an MLR Command Element in Hawaii directing live and virtual (piloted from linked simulators) F-35 Joint Strike Fighters located in Cherry Point, North Carolina, receiving targeting data for virtual enemy ships from a live Expeditionary Advance Base on San Clemente Island, California, transmitting targeting data to an Expeditionary Strike Group or executing a computer-generated naval strike missile attack, all with a shared and complete operational picture among all participants (USMC, 2023, p. 9).

Directed Action No. 15 in *Training and Education 2030* states,

> no later than (NLT) 1 September 2024, TECOM (supported by MCICOM and DC, I) will fully employ Project Tripoli as the means to develop a USMC, all-domain training construct that aligns with the Commandant's Planning Guidance and fully integrates training at all echelons. This capability will include a network architecture that integrates real-time data from ranges, devices, simulators, and constructive forces while enabling interaction between geographically dispersed Marine Corps, joint, and partnered nation units around the globe, achieving initial operating capability (USMC, 2023).

The Marine Corps continues to work towards determining the network architecture with research efforts supported by Project Tripoli. Within Project Tripoli, the Maritime Constructive Simulation (MCS) is the Marine Corps contribution to the Joint Live Virtual Constructive (JLVC) Federation. MCS, an improvement to the MAGTF Tactical Warfare Simulation (MTWS), provides "service-level simulation supporting division and higher command and control exercises" (USMC, n.d.). The Marine Corps operates the Aviation Distributed Virtual Training Environment (ADVTE) which provides network connection and is described as "a customized, persistent, closed-loop network enabling geographically dispersed flight simulators to participate in training events" (USMC, n.d.). ADVTE may provide the platform for adding systems to a single network using a common federation for additional systems to join.

In agreement with Mills's joint applied project, *Training and Education 2030* outlines the increased number of repetitions achieved by tactical and operational level warfighters with the use of LVC-TE. The Marine Corps established a program to continue developing LVC capabilities. The Marine Corps' Training and Education Command (TECOM) fulfills the role of providing further development for the LVC-TE and in 2023, Project Tripoli was created to support future development, empower stakeholders, and advocate for innovative LVC technologies. Project Tripoli was introduced in *Training and Education 2030* and is TECOM's primary means of advancing synthetic training environments to improve the quality of training for Marines and sailors across the Fleet Marine Force (FMF). Project Tripoli aims to meet joint LVC requirements for standards described in Department of Defense Instruction (DoDI) 8310.01 as well as guidelines for information assurance and support to computer network defense outlined by the Chairman of the Joint Chiefs Instruction (CJCSI) 6510.01F. Many of the issues identified by Mills in the joint applied project gap analysis regarding the LVC strategy for the Marine Corps are addressed by Project Tripoli.

3. Project Tripoli

Project Tripoli is the Marine Corps program designed to fully develop LVC-TE capabilities across the Marine Corps. Project Tripoli seeks to combine multiple platforms to improve training and simulation through a networked environment that integrates units across the MAGTF. The LVC-TE provides methods of conducting complex training in a way that prevents the ability of adversaries to monitor the exercises or experimentation. Figure 1 displays a graphical depiction of the desired scope of Project Tripoli.

Figure 1. Project Tripoli is the Marine Corps' Initiative to Provide a LVC-TE That is Persistent, Globally Available, All-Domain, and All-Echelon. Source: TECOM, PowerPoint slides, 2023.

The problem statement for Project Tripoli states:

> The Marine Corps' portfolio of simulations and ranges are designed for isolated, single purpose training applications, poorly positioned to support the integrated, scalable training environments necessary to enable the operating concepts and planned weapon systems envisioned in Force Design 2030. While high quality LVC training is available; limitations on time, technology, standards, and technical expertise reduce the availability of this training. Current LVC efforts are episodic and not fully integrated across all echelons in support of multi-domain operations (TECOM, PowerPoint slides, 2023).

Project Tripoli is exploring new AR/VR/XR technologies "to support enhanced individual and small unit training and increased training opportunities for high demand/ low density assets" (TECOM, PowerPoint slides, 2023).

Project Tripoli consists of subsections (a) through (l) and describe the efforts to combine platforms and people across an integrated network.

a. Transport Network

The transport network is an "enterprise-managed, wide area network (WAN) supporting a distributed infrastructure with centrally managed resources and cybersecurity connecting geographically dispersed locations across the world" (TECOM, PowerPoint slides, 2023). The Marine Corps WAN is one component of the Marine Corps Training Network (MCTN). The Marine Corps has not established the protocol for the WAN and Project Tripoli is the program identified to establish the network and network protocol. This network is critical to integrating all platforms across all locations.

b. Local Training Network

The local network supports the wireless networking needed on installations and in facilities. Systems will use the local training network (LAN) to connect to the WAN and eventually the Marine Corps Training Environment (MCTE) via the Navy Continuous Training Environment (NCTE) (TECOM, PowerPoint slides, 2023). The LAN requires investment to improve cyber security and wider dissemination of network infrastructure.

c. Force-on-Force Next Training System

The Force-on-Force Next Training System (FoFTS) Next will provide non-live fire training capabilities through a new suite of Marine Corps Tactical Instrumentation Systems (MCTIS) composed of a command and control (C2) network and systems (individuals, vehicles, and weapon surrogates) as well as low velocity training projectiles called the special effects small arms marking system (SESAMS) for individual and collective close quarters battle (CQB) techniques and procedures (TECOM, PowerPoint slides, 2023). The scope of the FoFTS-Next is expected to grow as new systems are acquired.

d. Tactical Video Capture System

The Tactical Video Capture System (TVCS) provides video recording of live range events. The suite of cameras is installed throughout the range complex providing overlapping coverage of camera field of view (TECOM, PowerPoint slides, 2023). The cameras record the actions of the Marines and sailors conducting operations in the range complex. The intent of the camera suite is to provide "video-based After-Action Review capabilities to support Marine Corps training at live-fire shoot houses, urban training environments, and infantry immersion trainers" (TECOM, PowerPoint slides, 2023).

e. Electromagnetic Warfare Ground Instrumented Range

Marines require better preparation for warfare in electromagnetic spectrum operations. The Electromagnetic Warfare Ground Instrumented Range (EWGIR) "directly injects a denied, degraded, and disrupted electromagnetic spectrum operations (EMSO) training environment. EWGIR augments live training for EMSO" (TECOM, PowerPoint slides, 2023).

f. Marine Constructive Suite

The Marine Constructive Suite will replace the MTWS (TECOM, PowerPoint slides, 2023). MCS is the constructive platform within the Marine Corps' LVC infrastructure. The Marine Constructive Suite supports division and higher until level command and control exercises. The upgrades to MTWS include modification of code from Ada to C++ (TECOM, PowerPoint slides, 2023). This upgrade improves the legacy system making it "efficient, flexible, and easier to integrate" (TECOM, PowerPoint slides, 2023).

g. Marine Common Virtual Platform

The Marine Common Virtual Platform (MCVP) is the common hardware and an end-user access point to the LVC-TE (TECOM, PowerPoint slides, 2023). The Marine Corps sees this capability as a computer or laptop. It is possible that a MCTP could also take the form of an AR/XR system. The AR/XR head-mounted system may be a compliment to the laptop. "MCVP will house applications at a local level, providing access to potential cloud solutions, to take advantage of concepts like edge computing" (TECOM, PowerPoint slides, 2023).

h. Joint Virtual Fires Trainer

To support training for controlling kinetic fires, the Marine Corps acquired the Joint Virtual Fires Trainer (JVFT) to replace the Supporting Arms Virtual Trainer (SAVT) (TECOM, PowerPoint slides, 2023). The JVFT is a "deployable system supporting training for aviation and surface-to-surface fires" (TECOM, PowerPoint slides, 2023). The Marine Corps intends to use the 3D Warfighter Augmented Reality (WAR) system along with the JVFT and other VR/AR common hardware.

i. Aviation Distributed Virtual Training Environment

The aviation community within the Marine Corps uses a networked simulation system that uses common middleware and software across a digital tactical environment (TEn) that links various aircraft simulators to support simultaneous aviation training with multiple simulators (TECOM, PowerPoint slides, 2023). The TEn is designed with virtual models of equipment and people of various designs that manifest in the virtual environment as friendly and enemy forces. All users, while active on the TEn and networked can see the virtual models. The benefit of the TEn and the ADVTE network is that the software maintains common entity enumerations across all simulation platforms through the TEn software. ADVTE is a common virtual environment built around a common software that can support other simulators and devices.

j. Ground Vehicle Training Systems

The ground vehicle family of systems includes the Driver Trainer (AAO 58), the Tactical Vehicle Crew Simulator (AAO 7), and the Reconfigurable Platform Simulator (AAO 1; TECOM, PowerPoint slides, 2023). The ground vehicle training system (GVTS) "provides driver trainers and tactical vehicle simulators for common vehicles found in the Ground Combat Element (GCE) and Logistics Combat Element (LCE)" (TECOM, PowerPoint slides, 2023).

k. Small Unit Tactical Training System

The Small Unit Tactical Training System (SUTTS) is a family of systems containing the Indoor Simulated Marksmanship Trainer (ISMT) which "focuses on small arms marksmanship, weapons familiarization and employment fundamentals, firing table practice, and supports call-for-fire and fire direction center training" (TECOM, PowerPoint slides, 2023). The Advanced Small Arms Lethality Trainer (ASALT) provides "advanced marksmanship training for individuals and small teams, in an enhanced environment, including instructor coaching, human-performance metric capture and analysis, enabling significant improvement in marksmanship skill for small teams and individuals through the FMF" (TECOM, PowerPoint slides, 2023).

l. 3d Warfighter Augmented Reality System

The Marine Corps, in partnership with the ONR, is exploring the use of the 3D WAR system to conduct training for surface to surface and air to surface based fire support. The WAR system provides increased training repetitions for the user with augment reality solutions. The user wears a head-mounted display that provides digital holographic overlays to the user. The overlays generate an environment where the user can practice conducting fire support with surface to surface and air to surface weapons (TECOM, PowerPoint slides, 2023). The WAR system was built with LVC in mind and seeks to scale joint fires training alongside the Joint Terminal Attack Controller (JTAC) Virtual Trainer (JVT) and Havik virtual reality-based training systems. Research on the use of the WAR system has been limited to fires coordination.

4. Accessing the Live, Virtual, Constructive-Training Environment

The Marine Corps has multiple devices to access the LVC-TE. The listed systems in Project Tripoli are access points. MCTP is a computer that provides the common access point to LVC-TE and provides methods for manipulating scenarios in software to create the training environment where all users participate in combined training.

AR/VR/XR systems provide a method of accessing the LVC-TE. Interoperability is required for AR/VR/XR systems, and their design must include accessibility across the enterprise of networks, systems, and software.

B. PURPOSE OF RESEARCH

I Marine Expeditionary Force (I MEF) sponsored funded research to identify a system that supports training and operations across various mission use cases. The need, as outlined in Naval Research Program Topic NPS-24-M225, specifically requests research on methods of hand and arm tracking for AR, VR, or XR systems. The request also seeks solutions for application development for the same systems. The end state seeks to modify an AR/VR/XR system for use in training and operation across a wide range of mission use cases within the Marine Corps. AR/VR/XR solutions can provide information in the form of projected data provided to the user from a digital headset that is wireless, network-enabled, geo-rectified, and supported by software that provides digital overlays or projected information to the user. Navigation-based sensors with geo-rectified digital graphics that overlay the user's geographic location frequently support AR devices. Headset cameras provide an opportunity to integrate computer vision (CV) technology via data labeling and supervised learning or machine learning. Mixed reality capabilities provide simulated virtual overlays and augmented reality cues while also allowing the user to see the surroundings of their environment. The research for this thesis assists in determining systems that provide augmented reality and mixed reality capabilities for various mission use cases in the Marine Corps.

1. System Needs

A single AR/VR/XR system that can provide every desired capability is not available and, if desired by the Marine Corps, would require an initial capabilities document (ICD), analysis of alternatives (AoA), and a material development decision (MDD). A capability development document (CDD) should be used to determine the requirements that would be needed by such a system in a major capability acquisition and a work breakdown structure (WBS) is required. At least one prime manufacturer, Microsoft, indicated that they are open to starting this process to develop a major capability in this space.

Without a major acquisition, the Marine Corps relies on commercial systems. The commercial device is then revised to support a specific use case. An example of this is an augmented reality system called the 3D WAR system under development by the ONR for fires training in the Marine Corps. The acquisition of commercial systems complicates the process of creating a unified ecosystem. The scope of desired use cases for commercial systems expands as the system is researched by organizations and laboratories. The expansion of the scope of desired capabilities with commercial systems means that independent and custom solutions to bridge the requirement gap are developed for each system. The lack of a unified requirement for all systems, software, and networks required to support those systems results in the siloed development of the system for a specific use case supported by contractors developing solutions to connect that system to the wider network, high level architecture, and federation.

Many devices in the commercial sector provide various capabilities, but merging every capability into one system has yet to be achieved. AR displays overlay reference data without looking away at reference materials such as a tablet screen, map, or document. AI can enable AR and assist with automated functions. A mixed reality use case is conducting maintenance, such as aircraft maintenance. Aircraft maintenance practices and supply chain management supporting aircraft maintenance integrate with data and provide better solutions using artificial intelligence. Commercial devices exist to overlay augmented reality displays to assist the user with real-time access to information while looking at objects that the data supports. Aircraft maintenance requires access to data provided by the currently fielded portable electronic maintenance aide (PEMA) in the form of a tablet or Toughbook. Using such devices while conducting maintenance is cumbersome and does not support the user seamlessly. Tablets and Toughbooks do not document maintenance actions. Maintainers using tablets or Toughbooks need systems integration that supports maintenance documentation or access to the systems that support the supply of parts and equipment necessary to conduct maintenance actions.

Augmented reality displays can overlay data that the user references in real time without looking away at a PEMA or a physical map. AI algorithms assist the user with the automation of functions, selection options, and data to perform different actions via an augmented reality wearable device. AI can assist aircraft maintenance with functions such as automation of supply-side functions, clustering of maintenance data for future capabilities, digital prompts for maintenance actions, CV for identifying parts, location of parts on the aircraft, and status of installations of the part on the aircraft. An example of supply automation is identifying the removal of parts for replacement through CV and then displaying a prompt for the user to order a replacement part in real-time. The user can also see prompts that support maintenance documentation, such as when the user is working on the component, performing actions, drafting maintenance action forms, and listing the work center conducting the maintenance on the maintenance action form.

Augmented reality and mixed reality systems, developed to include AI, could support multiple other mission use cases. Geo-rectified digital overlays can support different operation environments. Geo-rectified digital overlays can provide better training and support the simulation of different operating environments using the same training areas. Software development and digital design of varying simulation models can assist with creating digital capabilities to support a wide array of mission sets across multiple tactical and operational communities. In the aircraft maintenance use case, AI-enabled AR can source and provide access to mega-data accessed through the Naval Operational Business Logistics Enterprise (NOBLE) Naval Operational Supply System (NOSS).

The NOBLE NOSS is an Other Transaction Authority (OTA) funded contract and is still under development. "The U.S. Navy's NOSS program will support the Naval Operational Forces including Maritime, Aviation, Expeditionary, and Shore Support Units" (One Network Enterprise, n.d.). The cloud-based support infrastructure for naval supply makes AI-enabled AR integrated into NOBLE NOSS applicable to a broad array of weapon systems supported by NOBLE NOSS cloud software.

> NOSS provides enterprise-wide automation of supply, inventory, and financial functions to the naval supply system. NOSS will aggregate and analyze logistics data using business intelligence technologies, provide for total asset visibility, optimize business processes at the tactical echelon (field level) and enterprise support activities, accelerate the ordering/re-ordering process, and permit monitoring of shipments. NOSS will aggregate and analyze operational data in a business intelligence (BI) framework to enable a historical and predictive common operating picture of logistics and readiness performance and requirements (DOD, 2017, p. 24).

The Naval Aviation Maintenance System (NAMS) is a sub-component of NOBLE NOSS.

> NAMS will provide an enterprise-wide aviation maintenance capability that services all levels of aviation maintenance (organizational, intermediate, and depot) for over 2,100 Navy and Marine Corps aircraft. NAMS will identify and assign aviation artisans and track all levels of aviation maintenance to completion. Aircraft availability and mission capable rates can increase with the elimination of current inefficiencies (DOD, 2017, p. 24).

The data provided by NAMS will provide a database for reference to support the use of AR/VR/XR systems.

Integration of AR displays is the gateway to data supported by NOBLE NOSS and NAMS. Research will determine types of AI that can support digital wearable devices using CV. Three-dimensional (3D) mapping of components supports labeling to build the database, and CV can reference the built database of components to identify each part. The collection of 3D imaging creates a database that can provide typical applications across every weapon system and support building databases for every weapon in the arsenal.

Naval Aviation Logistics Command Management Information System for Organizational Maintenance Activities (NALCOMIS OOMA) and Optimized Intermediate Maintenance Activities (OIMA) require manual input for most data to support maintenance tracking and supply demands. As these systems move to NOBLE NOSS and NAMS, data will be available to support automated input of data via algorithms that can occur at the maintainer level in real time using augmented reality displays that provide prompts with selectable tasks. Observing the removal of components provides automated data entry into maintenance action forms.

Aviation maintenance is just a single example of a use case where AR/VR/XR may benefit the user. Other examples include, but are not limited to ground vehicle maintenance, aircraft pilotage, air and surface fires coordination and control, combat medicine, command and control, motor vehicle operations, infantry, load masters, helicopter support, and artillery.

2. Research Questions

The primary question guiding this research seeks to find a solution for I MEF that can assist with providing augmented reality capabilities across a wide range of communities within the Marine Corps.

- Research Question:

1. How can augmented reality, virtual reality, or mixed reality be used across a wide range of mission use cases within the Marine Corps?

- Supporting Questions:

1. How can AR/VR/XR headsets, using AI, be used to support mission use case functions?
2. How can training and operational use of the AR/XR headset be conducted?
3. How can AI support use case functions?

The research reviews various systems and identifies capabilities that the systems provide for the warfighter. The systems contain proprietary information due to the commercial nature of the systems. Access to proprietary information was restricted when evaluating these systems. Access to research laboratories where commercial systems are under development by commercial companies was restricted but laboratories that are supported by government funding were available.

C. THESIS STRUCTURE

The remainder of this thesis consists of Chapter II which covers the background of U.S. policy supporting this research and a brief review of AR/VR/XR use within the military. Chapter III includes the method for collecting the information and includes a baseline understanding of capabilities found in current and previous AR/VR/XR systems Chapter III assisted with determining methods of hand and arm tracking that are available with current AR/VR/XR systems as well as what to research regarding application developments for various use cases. Chapter IV includes results of data collected that support hand and arm tracking and application development for various use cases in the Marine Corps. Chapter V provides recommendations for future research and conclusions reached.

THIS PAGE INTENTIONALLY LEFT BLANK

D. POLICY GUIDANCE

The National Defense and Technology Strategy outlines the vision and goals for advancing science and technology to support national security and military advantage. The document lists strategic lines of effort, the joint mission, creating field capabilities at speed and scale, and ensuring the foundations for research and development (DOD, 2023). The document lists 14 critical technology areas that the U.S. Department of Defense (DOD) will invest in and protect to address the critical national security challenges and the pacing threat of China (DOD, 2023). The document groups the critical technologies into three categories: seed areas of emerging technologies, practical adoption areas with vibrant commercial activity, and defense-specific areas (DOD, 2023). The document emphasizes the need for rigorous analysis, joint experimentation, and technology protection to guide and safeguard the DOD's investment (DOD, 2023). Human-machine interfaces are listed as critical technology areas (DOD, 2023). The research in this thesis is supported by the National Defense and Technology Strategy.

> Any future fight will be a joint fight. The defense science and technology enterprise must collaborate with the Office of the Secretary of Defense Components, the Joint Staff, the Combatant Commands, the Defense Agencies, and the Military Services to accelerate the development of joint warfighting capabilities that address the key challenges described in the National Defense Strategy (NDS) (DOD, 2023, p. 2).

The U.S. DOD *Responsible Artificial Intelligence Strategy and Implementation Pathway* describes the responsible use of AI and its implementation across the DOD (DOD, 2022). The RAI strategy uses foundational tenets in developing the RAI strategy, including RAI governance, warfighter trust, AI product and acquisition life cycle, requirements validation, responsible AI ecosystems, and the AI workforce. One of the goals of the RAI strategy is to "create a repository of AI-related requirements for common use cases, mission domains, and system architectures to facilitate reusability" (DOD, 2022, p. 28). Implementing AI with AR capabilities in the Marine Corps must follow the RAI strategic guidance.

The Center for Naval Analysis (CNA) provides recommendations for the Marine Corps to consider. The CNA determines that the Marine Corps must make decisions using artificial intelligence and to do so, decision makers must begin learning about AI capabilities and technologies rather than depending on subject matter experts to provide adequate information for decision making. The use of technology through applications that provides an ability to better perform a targeted task is where military leaders must impose their guidance. What tasks need artificial intelligence integration and what is the method of accessing the AI based software?

> In this era of great power competition, it is imperative that the U.S. Marine Corps pursue AI rapidly and strategically. Marine Corps leadership must choose areas of exploration and investment wisely while simultaneously moving forward with needed enablers . . . Proceeding without sufficient understanding risks wasting crucial time and resources (CNA, 2021, p. 1).

The 2023 Global Trends in Artificial Intelligence Report conducts an analysis of AI adoption by reviewing use cases of successful AI projects. The research attempts to identify challenges that organizations face in scaling AI applications. The research focuses on the challenges imposed on AI application integration particularly when organizations have not updated their network infrastructure and data architectures (S&P Global, 2023).

E. REVIEW OF PRIOR MILITARY USE OF AR/VR/XR SYSTEMS

A Naval Postgraduate School thesis by Kacey Edward Kemmerer titled, "*Tactical Decision Making Under Categorical Uncertainty with Application to Modeling and Simulation"* analyzed response times when information is unclear to support training applications to reduce response time via modeling and simulation (Kemmerer, 2008). The thesis states the "Network Centric Warfare approach to command and control emphasizes decentralized decision-making . . . The results indicate that uncertainty and scenario difficulty are significant factors in determining response time" (Kemmerer, 2008). "[Human Systems Integration] aims to incorporate human systems in the 'systems of systems' architecture; it attempts to remedy an individual's weaknesses and highlight their strengths" (Kemmerer, 2008).

A Naval Postgraduate School thesis written by Lowell J. Dixon titled "*Shipboard 3-M program Supplemented by AR Technology"* explores the use of AR in Naval ship maintenance (Dixon, 2022). The thesis discusses how inefficiencies in maintenance practices effect readiness (Dixon, 2022). Maintenance actions and requirements for readiness are no different for Naval and Marine Corps aircraft as well as other systems. As mission difficulty and pace increase, these programs must reduce errors and improve efficiency. "AR technology can be used to identify and label all components in a space to assist with correctly identifying equipment and provide virtual instructions with critical, step-by-step information for conducting maintenance inspections, repair work, and Damage Control (DO) events" (Dixon, 2022).

Funded research conducted by Amir H. Etemadi and John Kamp (2022), through a research grant with the Acquisition Research Program at the Naval Postgraduate School, discusses the Army's Integrated Visual Augmentation System (IVAS) (Etemadi et al., 2022, May 13). The IVAS is an augmented and mixed reality wearable headset for the Army that supports the infantryman. The research conducts a historical analysis of the development of the IVAS. The report reviews AR development and entangles the incorporation of AR into military use cases (Etemadi et al., 2022, May 13). The IVAS is a middle tier acquisition (MTA) project under development by the Army in conjunction with Microsoft (Etemadi et al., 2022, May 13). The IVAS is a modified HoloLens 2 system that integrates into the vest of the Army soldier. Using the MTA pathway reduces the time to acquire systems by taking advantage of commercial systems. The IVAS experienced several developmental issues early in the acquisition life cycle (Etemadi et al., 2022, May 13).

The Havik Core system is a head-mounted virtual reality device supporting combined arms training. The hardware includes computer stations, flight simulation stations, headsets, and hand wands.

The Office of Naval Research is working on the JVT and the 3D WAR system.

> The JVT is a virtual reality system that moves virtual reality training from a fixed dome and screen site for training toward a mobile kit-based approach that uses a commercial gaming engine in concert with a highly realistic head-mounted display and associated hardware packaged in a

> form factor that fits into a one-person portable pelican case and can interoperate with existing Program of Record tactical training software . . . The 3D WAR system is an augmented reality device with a backpack computer processor, head-mounted display, and navigation sensor supporting augmented reality digital projections across a real-world environment. This system can function in multiple locations on the ground and while aboard a ship (Duffie, 2021).

The Naval Research Laboratory researched the Battlefield Augmented Reality System (BARS). "The initial BARS prototype consisted of a different kinematic GPS receiver, an orientation tracker, a head-worn display, a wearable computer and a wireless network" (Rosenblum et al., 2012). The computer creates graphics that seem to align perfectly with the real environment from the user's perspective (Rosenblum et al., 2012). For instance, AR can superimpose images onto a building to display its name (Rosenblum et al., 2012). The BARS program is covered in more detail in Chapter III and provides the historical development of AR applications for military use in the Navy and Marine Corps.

The Defense Advanced Research Projects Agency (DARPA) funded research in a developing technology called Perceptually Enabled Task Guidance (PTG) (DARPA, 2021, March 5). DARPA describes the PTG program in the following way.

> The PTG program aims to develop artificial intelligence technologies to help users perform complex physical tasks while making them more versatile by expanding their skill set and more proficient by reducing their errors. PTG seeks to develop methods, techniques, and technology for artificial intelligence assistance that provide just-in-time visual and audio feedback to help with task execution. The goal is to provide users with wearable sensors that allow the assistant to see and hear what they see (Marge, 2023).

PTG works with an augmented reality headset that assists the user by providing audible and visual instruction. CV significantly improves augmented reality capabilities with an exquisitely designed data set.

Previous research on the use of AR/VR/XR in the Navy and Marine Corps includes concepts surrounding specific capabilities used to support a community, such as the Navy's Center for Security Forces (CENSECFOR). The thesis reviewing AR/VR/XR capabilities supporting CENSECFOR titled *How can the Center for Navy Security Forces*

Leverage Immersive Technologies to Enhance its Current Training Delivery? focused on cost reduction of training (Sanders et al., 2018).

Research is available on using AR/VR/XR systems to conduct multiple maintenance use cases (Mustapha et al., 2021). AR/VR/XR capabilities can assist in performing maintenance and training maintenance personnel. Cost savings analysis shows where AR/VR/XR capabilities would benefit maintenance actions and training (Mustapha et al., 2021). Multiple publications support using AR/VR/XR for military applications, but the focus on using AR/VR/XR capabilities within the Marine Corps for use cases outside of aviation and fires support communities is not readily available.

THIS PAGE INTENTIONALLY LEFT BLANK

METHOD

During the conduct of this research, AR and XR systems were considered for both training and operational purposes. AR and XR systems provide see-through capabilities that can be used outside of the training environment and the use of these systems was considered for operational use cases in addition to supporting training. VR was considered for training purposes.

F. SYSTEMS IDENTIFIED

I MEF provided guidance for this research in the Naval Research Program research proposal titled *Virtual Reality and Augmented Reality Applications*. Guidance consisted of identifying methods of hand and arm tracking as well as methods of developing software applications that support various use cases for AR/VR/XR systems. To begin identifying these methods, it was necessary to study systems that are already developed, commercially available, and have been previously researched to assist with determining a baseline for available technology.

Systems identified provide the user with a heads-up display by wearing a head-mounted device that provides image projection in front of the user. The researcher reviewed multiple AR/VR/XR systems that are in the commercial sector and have been or are under development by various research laboratories.

1. Virtual Reality Systems

a. Havik

Research was collected on the Havik system by communicating with the Naval Research Laboratory as well as referencing materials from the manufacturer.

The U.S. Special Operations Command (SOCOM) adopted the Havik's virtual reality simulation platform that supports call for fire (CFF) and close air support (CAS) training. Havik VR is a head-mounted device that places the user in a virtual environment that simulates a geographic location and provides virtual models of targets, aircraft, and weapon systems. The user can build a scenario to replicate a variety of tactical scenarios to practice tactics in accordance with the Multi-Service Tactics, Techniques, and Procedures for the Joint Application of Fire Power and the Joint Publication 3-09 Joint Fire Support Publication.

Havik is the only simulator that is certified for conducting qualification producing training for JTACs in SOCOM (Wagoner & Satanek, 2021). Havik provides two systems, Havik Core and Havik Atlas. Havik Core, displayed in Figure 2, provides a laptop computer system with software that integrates into the Android Tactical Assault Kit (ATAK). The software provides the user with options to generate tactical scenarios that are immersive. Havik core also contains a VR headset and a set of two handheld wands for user input while wearing the VR headset. Hand and arm tracking is provided by the wands. Havik Core uses Unity video game software for the development of its application.

Figure 2. Havik Core Contains a VR Headset, a Set of Wands, and a Computer for Building Scenarios. Source: Havik (n.d.)

The Havik Atlas System, displayed in Figure 3, provides multiple Havik Core systems that are networked. Havik Atlas networks aircraft simulators via a distributed interactive simulation (DIS) per the Institute of Electrical and Electronics Engineers (IEEE) standard. Havik Atlas also uses the common image generator interface (CIGI) to support networking simulator devices. To use the Havik Atlas system with Marine Corps aircraft simulators the software will require compatibility with the Marine Corps' ADVTE and TEn.

Figure 3. Havik Atlas System Displaying Networked Havik Core and Flight Simulator. Source: Havik (n.d.)

b. Joint Terminal Attack Controller Virtual Trainer

The ONR is conducting research on the Joint Terminal Attack Controller (JTAC) Virtual Trainer (JVT) for the Navy and Marine Corps. The research supports certifying the JVT for standard training that can provide JTAC qualifications. Data was collected from ONR and Xiphos Partners on the JVT system.

The JVT, displayed in Figure 4, is compatible with Virtual Battlespace 3 (VBS3) and Modern Air Combat Environment (MACE). The JVT system is compact and provides a head-mounted VR device with a set of hand wands that track hand movement and provide input functions to the user. The JVT system supports call for fire and close air support training. Users are immersed in a virtual simulation. Tactical scenarios are developed that provide virtual targets, personnel, and equipment.

Figure 4. The JVT System Provides a Head-Mounted VR Device, a Set of Wands, and Software for Generating Immersive Training Scenarios for the User. Source: Xiphos Partners (n.d.)

The JVT can link with other virtual trainer systems via a DIS or high level architecture (HLA; Xiphos Partners, n.d.). The JVT has video pass through capabilities allowing the user to see the outside world in addition to the virtual simulated environment. Havik Atlas requires compatibility with common Marine Corps software for interoperability with the Marine Corps' ADVTE and TEn.

2. Augmented Reality and Mixed Reality Systems

a. Battlefield Augmented Reality System

Information and data were collected from the NRL on the BARS, the history of its development, and practical application for military use.

The BARS was a program that began in the Fall of 1998 with the NRL (Feiner et al., 1997). The research conducted by the NRL ended in 2012. The BARS started with a wearable system called the Columbia Touring Machine, displayed in Figure 5, designed by researchers at Columbia University that consisted of a backpack supported by a frame design and linked to a head-mounted display that provided see-through capability with digital graphic displays projected in front of the user (Feiner et al., 1997). The user manipulated the graphic displays with a stylus pen and tablet that interfaced with the head-mounted displays (Feiner et al., 1997).

Figure 5. The Columbia Touring Machine in 1997. Source: Feiner et al. (1997).

The ONR worked to improve this technology to “generate 3D virtual worlds that would be viewed through head-tracked displays” (Rosenblum et al., 2012, p. 1). Rosenblum and Livingston continued the research and, through Naval Research Laboratory funding, established the BARS. The BARS, displayed in Figure 6, provided a wireless input device, see-through display, camera, audio headset, orientation tracker, global positioning system (GPS) antenna, wireless network antenna, GPS receiver, embedded computer, and battery.

Figure 6. The Battlefield Augmented Reality System (BARS) Depicted with Each of the System Sub-Components. Source: Brown et al. (2005)

The BARS provided foundational experimentation for the use of AR while the user is mobile and operating in outdoor environments. Research used by the BARS program included algorithms that assisted in determining what functions are most relevant for the user (Rosenblum et al., 2012). The BARS incorporated research from previous studies identifying methods of tracking head position relative to the real-world operating environment, clarity of reading text in outdoor daytime environments, as well as graphical parameters, depth perception measurement techniques, and view management placing labels onto objects (Rosenblum et al., 2012). The BARS program developed an application architecture that was demonstrated in 2004 at Marine Corps Base Quantico. The demonstration used the application to provide the user with graphical overlays that mimic targets that can be used for practicing call for fire (Rosenblum et al., 2012).

In 2012, the Naval Research Laboratory discontinued research on the BARS. Commercial technology improved augmented reality development and the Naval Research Laboratory, along with the Marine Corps, moved on to the Augmented Immersive Team Trainer (AITT).

b. 3D Warfighter Augmented Reality System

The ONR is conducting research on the 3D Warfighter Augmented Reality (WAR) system to support training for fire support teams (FiST), forward observers (FO), joint fires observers (JFO), and JTACs (Duffie, 2021). ONR funded research on 3D WAR and the Marine Corps is working in partnership with ONR to integrate 3D WAR as a component of Project Tripoli. The use of 3D WAR is focused on fires training, specifically CFF and CAS.

3D WAR is a product of Lockheed Martin and SRI International.

> The 3D WAR system is an augmented reality device with a backpack computer processor, head-mounted display, and navigation sensor supporting augmented reality digital projections across a real-world environment. This system can function in multiple locations on the ground and while aboard a ship (Duffie, 2021).

Experimentation with the 3D WAR system includes evaluating Marines while conducting training with both live fire and simulated fire on live range facilities. 3D WAR provides digital models that are projected in front of the user. As opposed to video pass through, the user can see through the head-mounted display to observe the outside world while digital models are overlayed against the actual terrain.

The 3D WAR head-mounted display can be seen in Figure 7. Marines in Figure 7 are conducting CAS and viewing digital models of targets. Figure 8 depicts what the user sees when using the head-mounted display. The images are digital overlays of target locations. A compass rose is displayed at the top of the field of view assisting the user with increased situational awareness of direction. The CAS 9-line number with final attack heading and time on target for the respective 9-line attack brief is displayed in the bottom right corner of the field of view. A digital overlay of the Kilswitch application is viewed in the bottom left corner. Additional digital overlays can be provided including video feeds from airborne sensors.

The 3D WAR system operates on the AITT federation object model (FOM) and uses HLA 1516. It is compatible with the ADVTE FOM. Unity is used for the design and development of the presentation layer. ONR funding provides continuous research on the 3D WAR system with a focus on CFF and CAS use cases. ONR has not researched additional use cases for the 3D WAR system.

Figure 7. 3D Warfighter Augmented Reality System Head-Mounted Display Worn by Marines at Marine Corps Base Quantico Conducting Simulated Call for Fire. Source: Office of Naval Research (2022).

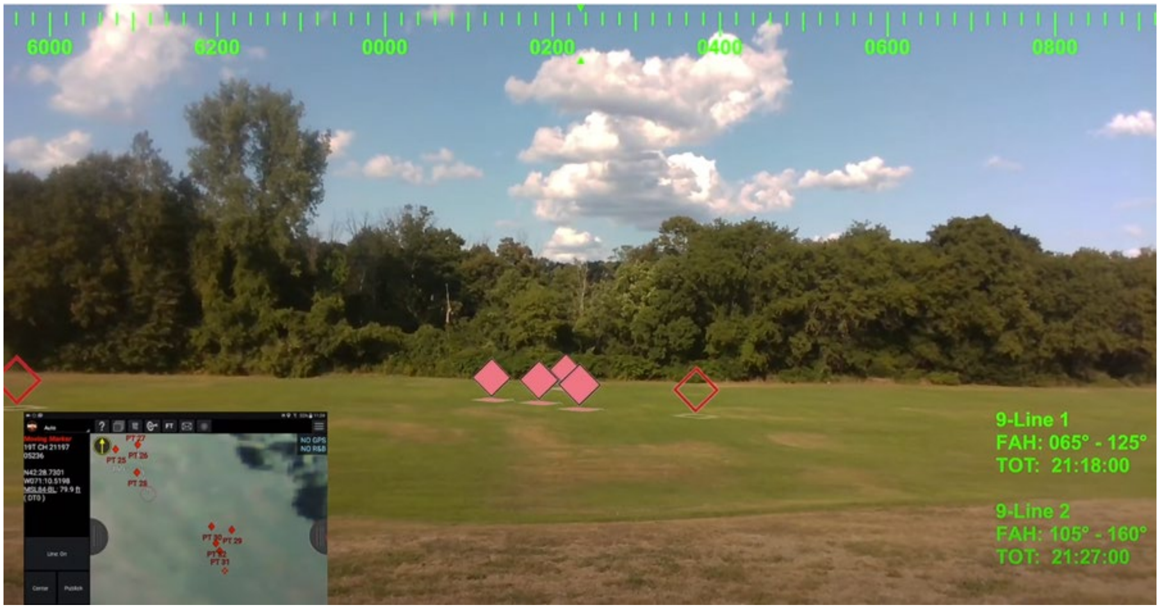

Figure 8. Augmented Reality Digital Overlays Provided by the 3D WAR Head-Mounted Device Depicting the Location of Enemy Targets Supplemented by a Compass Rose Header, CAS 9-Line Details, and Imagery Overlay from the Kilswitch Application. Source: Office of Naval Research (2022).

c. Quest

Quest 3 is a commercially available mixed reality head-mounted system developed by Meta. Meta's Reality Labs continues to engineer improvements to the Quest design. The head-mounted device provides two ocular windows that are adjustable, both in distance of the screens from your eyes and the interpupillary distance of the windows. Quest 3 uses the Snapdragon XR2 Gen 2 with the next-gen Qualcomm Adreno GPU and the Kryo CPU (Qualcomm, 2024). Quest 3 combines VR and XR capabilities into a single hardware architecture that reduces the overall size and weight of the head-mounted device. The Snapdragon XR2 Gen 2 supports AI and has CV hardware.

Quest 3, displayed in Figure 9, uses video passthrough to provide the user with an immersive experience when wearing the head-mounted device. The video passthrough projects the image of the environment around the user into the user's field of view. Cameras mounted on the frame of the headset provide video footage. The cameras provide CV capabilities. Quest is a network enabled device with the Qualcomm FastConnect 7800 Mobile Connectivity System that provides Wi-Fi 7 (Qualcomm, 2024).

Meta continues to develop the Horizon operating system (OS) with the intent of providing an open architecture that supports additional hardware systems. Meta's focus on the operating system with an open architecture that supports the integration of additional hardware is a practice that benefits the Department of Defense.

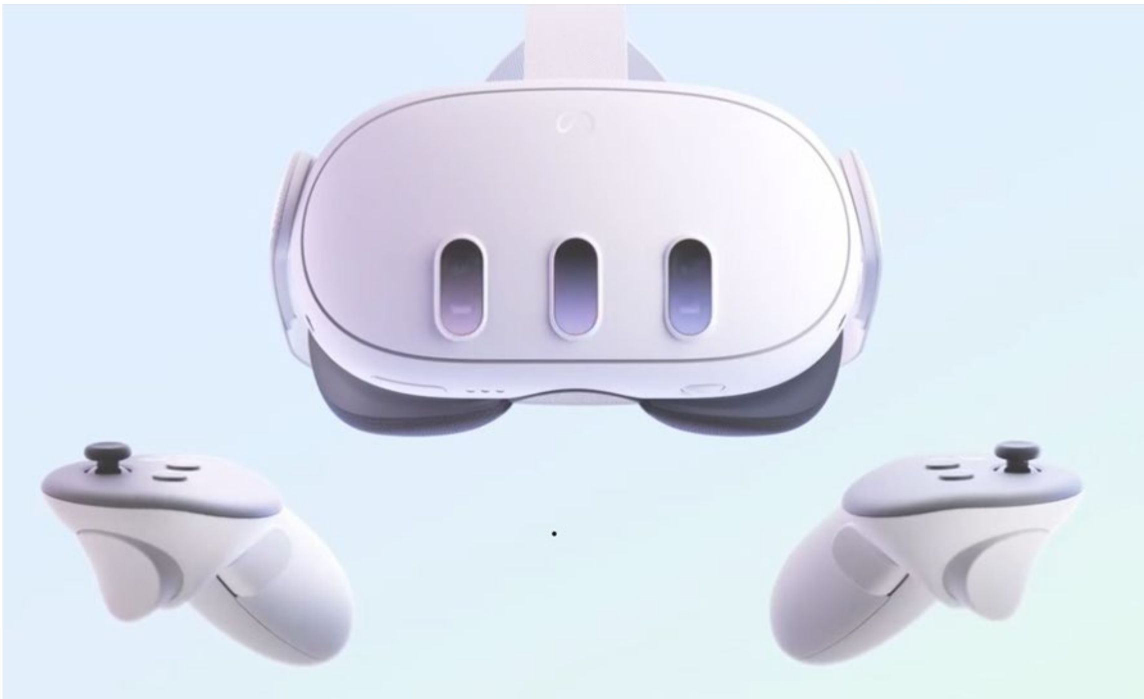

Figure 9. Quest 3 Head-Mounted Display with Two Hand Control Wands. Source: Meta (n.d.).

d. Integrated Visual Augmentation System

Research on the IVAS was conducted with the assistance of the IVAS team at Microsoft.

The IVAS is an AR and XR system for Army infantry soldiers. The IVAS is designed for the soldier. Experimentation for the IVAS is focused on supporting the infantry but can support other use cases by modification of software applications. The Army's Soldier Lethality Cross Functional Team (CFT) continues to work on improvements in the IVAS design alongside Microsoft. Microsoft is the prime manufacturer of the IVAS, and the Army contracted a fixed-price production agreement with Microsoft. OTA contracts have provided funding for IVAS development since 2018. Specifically, the Army issued an Other Transaction-Indefinite Delivery Vehicle (IDV) in

2018 and the initial obligation was $215,638,968.76 (Federal Procurement Data System, 2018).

The Army has continued to use OTA contracts for additional rounds of funding to support the development of the IVAS. As of April 2022, the total obligation for the OT-IDV for the development of IVAS is $641,161,773.08 (Federal Procurement Data System, 2019). Microsoft developed and tested version 1.0, 1.1, and now 1.2. The Army continues to push for an initial purchase lot of the IVAS. In fiscal year (FY) 2023, the defense authorization bill reallocated funding of $40,000,000 from the Army's night vision devices procurement to provide continued work on the IVAS 1.2 design (Beinart, M., 2022). In the FY 2024 defense authorization bill, Microsoft was awarded $95,000,000 for delivery of 280 pre-production IVAS 1.2 models for testing in 2024 and operational testing in 2025 (Harper, J., 2023). Version 1.0 and 1.1 will not be purchased for fielding by the Army.

The IVAS 1.2 can be seen in Figure 10. The system has a suite of cameras that provides a low light sensor and a thermal camera. Both the low light sensor image and the thermal sensor image can be overlaid on top of each other to provide an enhanced image in degraded visibility or night environments. The quality of the image is high definition (HD) 1280 resolution. The image quality in low light, night environments is clear and with the thermal sensor, the user can see through smoke and dust environments.

The IVAS has a translucent display for daytime use and a video pass through display for night operations allowing the user to see the real-world while wearing the head-mounted display. Digital images are projected in front of the user in a 70-degree field of view. The IVAS provides various capabilities including digital playback of the actions performed by all users in a scenario. Playback is provided by a 3D graphic replica of the digitally mapped environment where the user can watch the playback of actions for conducting debriefs. Holographic displays projected in front of the user provide opportunities to train in identifying targets and firing at the targets. The translucent pass through allows the user to see the digital overlays and the real-world environment.

The IVAS design has continued to improve. Added capabilities include an artificial horizon to assist with orientation, improved reprojection color, a vertical display alignment tool, and variable focus all for maximum visual comfort. The IVAS can incorporate AI algorithms to assist with the use and function of the system. An example includes an AI algorithm that chooses what image should be displayed from the thermal sensor and what image should be displayed from the low light sensor. The body-borne computer pack, also called a puck, is now mounted on the back of the Kevlar helmet and provides better weight distribution to reduce discomfort on the neck for the user. The system fully integrates into the combat kit of the soldier, including the battery pack and hand controller. The IVAS is compatible with standard military radios and provides audible sound to the user via radio transmission.

Figure 10. Microsoft Integrated Visual Augmentation System 1.2 Worn by a U.S. Army Soldier During a User Touchpoint in August 2023. Source: Harper (2023).

The IVAS is network capable and supported by the cloud. The ability to network supports access to integrated data received from and transmitted to various systems connected on the network and provides the user with the location of other users. Identification of other users is provided by digital cues of their location, even when you cannot see the other user. The heads-up and hands-free manner of use provides the ability to track the location of each of the friendly forces when they are located behind a building or concealed in defilade. IVAS is cloud enabled but not cloud dependent and can integrate with a mobile ad hoc network (MANET).

The XVIII Airborne Corps is working with the Army Program Executive Office (PEO) Soldier to focus the IVAS use case around C2. This use case supports a variety of

C2 functions including command operation center (COC) tasks. One of the primary considerations for the exploration of the C2 use case is reducing the footprint required for a COC. A COC, displayed in Figure 11, is structured with computer stations that have multiple monitors per computer, projectors, screens, and all associated hardware. The size and scale of a COC varies by each unit, but the logistical footprint and power necessary to run a COC is significant. Using an AR device can reduce the footprint necessary to operate a COC. AR devices can also provide novel methods of accessing classified data in varying environments. The Army is working with Microsoft to include IVAS in the C2 Next program which seeks to integrate data collected through command and control.

Figure 11. U.S. Air Force Command Air Operations Center with All Associated Hardware. Source: United States Air Force (n.d.)

The IVAS uses Unity for the presentation layer and development of digital imagery. Unity is a common AR development platform and is also used by many other AR devices including 3D WAR. The Army is investing in a software development kit (SDK) that seeks to expand the use of IVAS and provide greater extensibility for the system for use with different applications. The software development kit will enable the Army to expand the use of IVAS for soldiers that are not infantry across multiple other military use cases.

The Army has invested, and continues to invest, significantly into the IVAS platform and has awarded a contract to Microsoft for up to $21.4 billion if fielded and fully executed (Blanchard, 2021). In 2018, the per unit cost for each IVAS unit was $3,500 (Blanchard, 2021). Re-engineering of the system has added additional cost, and it is expected that the per unit cost will rise when the system is ready for full-rate production.

G. APPLICATION DEVELOPMENT WITH PERCEPTUALLY ENABLED TASK GUIDANCE

1. Perceptually Enabled Task Guidance Overview

DARPA provided access for the author to several laboratories to research PTG technology. PTG is researched by a variety of academic and industry laboratories. The Massachusetts Institute of Technology (MIT) Lincoln Laboratory provides oversight on the performance of each academic and industry laboratory exploring PTG for various use cases.

DARPA is researching the application of AR assisted with AI for various use cases in the military. The project, called PTG, combines AR with AI through CV-based algorithms to provide instruction to the user for assisting with various tasks. PTG uses cameras mounted on AR headsets. The cameras observe what is occurring in the field of view. The cameras capture video of the actions taken. The video footage is referenced with a CV algorithm that determines the actions that are being taken within the video field of view. Data sets are labeled to assist the algorithm with recognizing what is occurring and then provide instructions to the user once the action is identified. Several laboratories are exploring PTG technology with the assistance of Microsoft's HoloLens 2 which can be seen in Figure 12.

Figure 12. Microsoft's HoloLens 2 Supports the Development of PTG Technology. Source: Raytheon BBN (2023).

2. DARPA PTG Program Structure

DARPA's PTG program seeks to find "novel approaches and integrated technologies that address four key problems" (DARPA, 2021). The key problems are listed in the DARPA Broad Agency Announcement titled, *Perceptually Enabled Task Guidance (PTG)*. The key problems include:

> 1. **Knowledge Transfer.** Assistants need to automatically acquire task knowledge from instructions intended for humans, with an emphasis on checklists, illustrated manuals, and training videos
> 2. **Perceptual Grounding**. The objects, settings, actions, sounds, and words recognized by an assistant must be aligned with the terms it uses to describe and model tasks, so that observations can be mapped to its task knowledge
> 3. **Perceptual Attention.** Assistants must pay attention to percepts that are relevant to current tasks, while ignoring extraneous stimuli. Assistants must also respond to unexpected, but salient, events that may alter a user's goals or suggest a new task.
> 4. **User Modeling.** Assistants must determine how much information to present to a user and when to do so. This requires an epistemic model of what the user knows, a physical model of what the user is doing, and a model of their attentional and emotional state. (DARPA, 2021, p. 5)

a. Technical Areas

(1) Technical Area 1

"Technical Area 1 (TA1) is for fundamental research into knowledge transfer, perceptual grounding, perceptual attention, and user modeling" (DARPA, 2021, p. 5). TA1 research is scheduled for the first 24 months of the 48-month study (DARPA, 2021). "The goal is to create PTG systems that process first-person sensory streams, meaning input from head-mounted cameras and microphones, and interact with users through AR headsets" (DARPA, 2021, p. 7). The use case listed for development by DARPA for TA1 includes the cooking domain (DARPA, 2021, p. 8). TA1 development includes logic-based symbolic reasoning, enhanced semantic graphs, and neural networks.

A single team dispersed between laboratories at the University of Texas Dallas, University of Florida, University of California Irvine, and University of California Los Angeles are researching logic-based symbolic reasoning. Five different teams dispersed between University of California Berkeley, Columbia, University of Texas Austin, University of Rostock, University of California Santa Barbara, Patched Reality, Stony Brook University, New York University, Texas A&M University, and Topos Institute are researching enhanced semantic graphs. A single team dispersed between University of Michigan, Purdue University, and University of Rochester are researching neural networks and their application to PTG.

(2) Technical Area 2

Technical Area 2 (TA2) performers are tasked,

> to produce militarily-relevant prototypes of perceptually-enabled task guidance systems to be used and evaluated by military service members. These prototypes should combine state-of-the-art perceptual, reasoning, and augmented reality technology with new technologies for knowledge transfer, perceptual grounding, perceptual attention, and user modeling developed by TA1 performers (DARPA, 2021, p. 9).

TA2 includes focusing on mechanical maintenance, battlefield medicine, and pilot assistance.

TA2 performers for PTG include the company, Redshred conducting mechanical maintenance, Raytheon BBN conducting battlefield medicine, and Northrop Grumman conducting pilot assistance. TA2 performers are developing prototypes that include "perception, reasoning, and AR components that may be modeled on pre-existing technology" (DARPA, 2021, p. 9). TA2 is scheduled for the second 24-month period of the 48-month study and is currently under development (DARPA, 2021).

(3) Technical Area 3

Technical Area 3 (TA3) will consist of a government evaluation team that will "create specialized demonstration scenarios for the cooking use case and for the military use cases defined by TA2 performers" (DARPA, 2021, p. 10). Table 1 describes the demonstration scenarios.

Table 1. The PTG Milestone Development Schedules Multiple Scenarios That Will be Evaluated by TA3 with TA1 and TA2 Use Cases. Source: DARPA (2021).

	Scenario #1	Scenario #2	Scenario #3	Scenario #4
Description	Monitor users performing one task, warn about mistakes.	Monitor users performing five interleaved tasks.	Walk users through 1 of 10 novel (to them) tasks.	Answer questions while monitoring users on up to 50 tasks.
Performance Target	Error recognition with F1 > 0.75	Error & task recognition with F1 > 0.75	Faster task completion, user acceptance	Faster tasks, fewer errors, user acceptance
Use Case	TA1: cooking TA2: military	TA1: cooking TA2: military	TA1: cooking TA2: military	TA1: cooking TA2: military
Evaluator	TA3 team member	TA3 team member	Military user (TA2 only)	Military user (TA2 only)
Schedule (in months)	TA1: 12 TA2: 18	TA1: 24 TA2: 30	TA1: 36 (opt.) TA2: 39	TA1: 48 (opt.) TA2: 48

b. Program Schedule

DARPA planned a period of 48 months to support the development of the PTG program. The first 24 months schedules Phase 1 and includes the TA1 development. The last 24 months schedules Phase 2 and includes TA2 development. The goal for the PTG program schedule is to have iterative touchpoints for evaluation during each phase. TA1 developers continue to improve their models by collecting data during TA2 development.

DARPA has yet to identify the TA3 performance group to evaluate the PTG use cases. The ONR, the NRL, and the Marine Corps would benefit from participating in TA3 evaluations to better understand the use of CV and PTG for assisting with conducting tasks across various use cases. The overall schedule for PTG in Phase 1 and 2 is depicted in Figure 13.

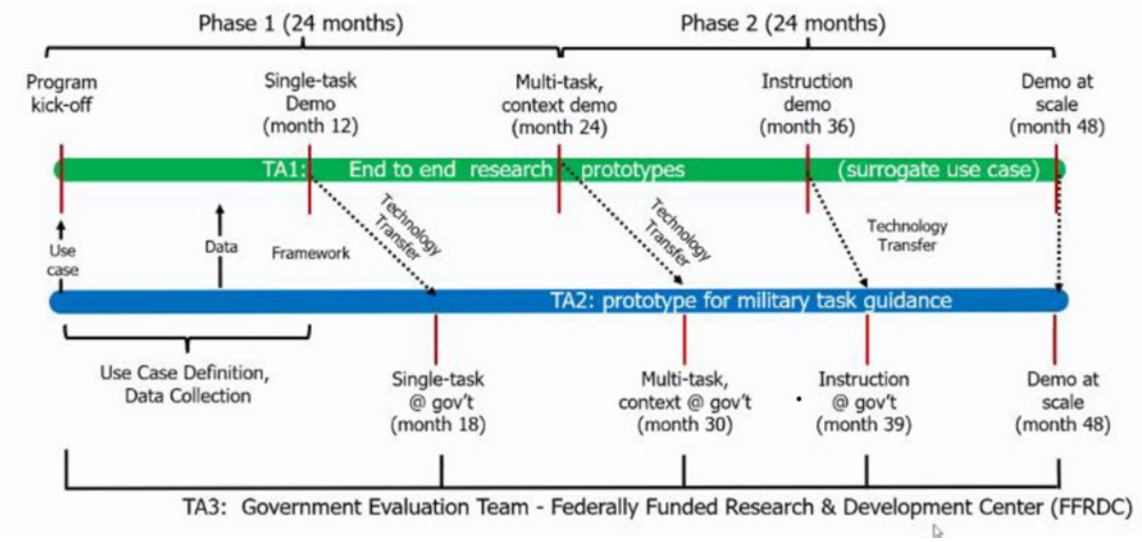

Figure 13. PTG Development Phases Include TA1 and TA2 Development. Source: DARPA (2021)

H. SITE VISITS

Site visits conducted during this research supported the collection of data on varying systems. Three site visits were conducted to collect information. Two site visits supported collecting information on PTG and a single site visit supported collecting information on a mixed reality system designed for military application.

The first site visit location was at the Redshred laboratory in Baltimore, Maryland to investigate the maintenance use case for PTG. Redshred is designated a TA2 performer in the PTG program and has developed a program called COACH. COACH was developed to meet the PTG maintenance use case program requirements. Redshred demonstrated the system during this site visit.

The second site visit location was at the Raytheon BBN laboratory in Minneapolis, Minnesota to investigate the tactical combat casualty care use case for PTG. Raytheon BBN is designated a TA2 performer in the PTG program (Raytheon, 2023). Raytheon BBN developed a system called MAGIC that assists with providing instruction to the user for tactical combat casualty care (Raytheon, 2023). Raytheon BBN demonstrated the system during this site visit.

The author visited Microsoft Corporation in Reston, Virginia for the third site visit. Microsoft demonstrated the IVAS during the site visit and discussed the features of the system and future development. Microsoft demonstrated the IVAS capabilities and provided additional information on the development of the IVAS hardware and software.

THIS PAGE INTENTIONALLY LEFT BLANK

RESULTS

I. PERCEPTUALLY ENABLED TASK GUIDANCE

DARPA is researching PTG to establish proof of concept. PTG uses AI to support the user by identifying actions from the perception of the user and then providing task guidance (DARPA, 2021). PTG is adaptable to a range of use cases and can support the user both in training and operations.

PTG uses CV with AI algorithms supported by data labels to identify the actions that are seen within the camera's field of view. The PTG program uses the Microsoft HoloLens 2 head-mounted display for experimentation. Other AR/VR/XR systems can be incorporated into PTG development. During experimentation, hardware limitations and processing speed have been challenges in the development of the technology.

The goal of the PTG program is to develop just-in-time feedback to the user to support complex tasks in real time. The device, or head-mounted display, will see and hear what the user sees and hears. AI will determine what actions are occurring and then provide the necessary information to assist the user with the exact task (DARPA, 2021). The focus for the PTG program is the development of AI. The scope of the program is not the development of hardware that is needed to use PTG AI technology. The concept is agnostic to any single piece of hardware.

PTG is different than augmented reality or mixed reality alone. The inclusion of AI via CV supports the user with an AI supported assistant, identifies the task occurring, and provides detailed instructions as the user is completing the task. PTG is scalable across a wide range of use cases. Raytheon BBN is developing a use case for combat medicine and the point of view for the user applying a torniquet can be seen in Figure 14.

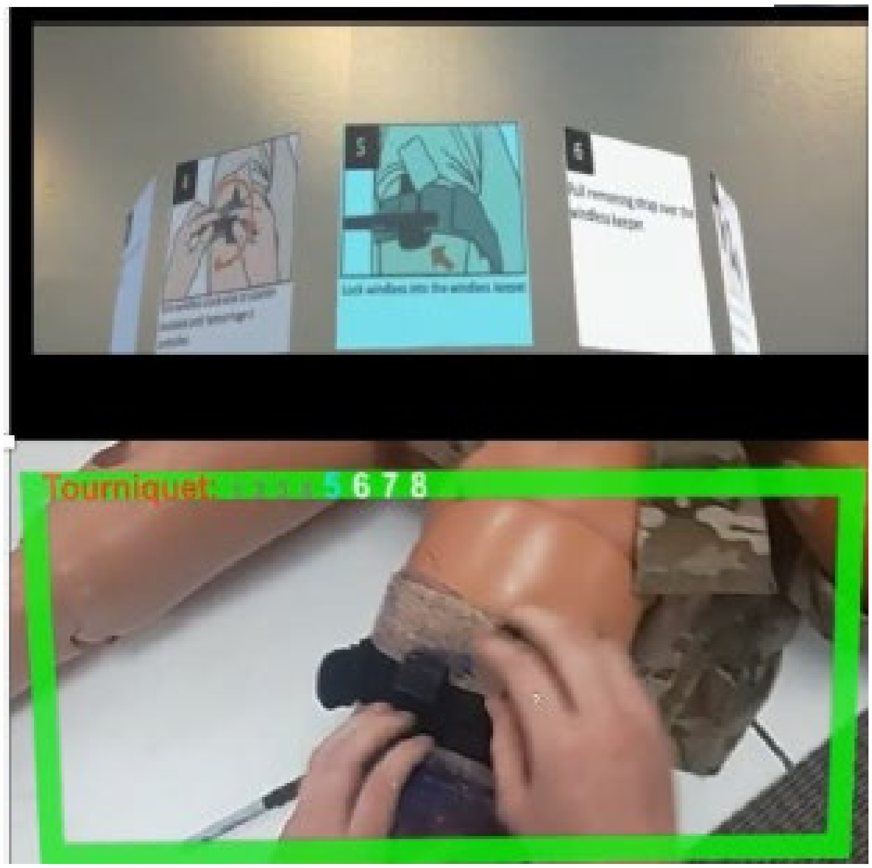

Figure 14. CV Identifying Step 6 of Applying a Tourniquet. The Carousel Shown Above is Available to the User as an Instructional Guide. Source: Raytheon BBN (2023).

1. Computer Vision

Using human's vision as a comparison, CV uses cameras that see and sense the world much like human vision. CV is intended to assist the computer with seeing items that are stored as data and are labeled appropriately to identify the image. CV conducts analysis of images to decern the image. The analysis is occurring rapidly and referencing many different data points to properly identify the object within view (IBM, n.d.a). CV uses convolutional neural networks (CNN) to architect image classification. The greater the number of convolutional layers, the more detailed the solution for identification.

> A convolutional layer is the first layer of a convolutional network. While convolutional layers can be followed by additional convolutional layers or pooling layers, the fully connected layer is the final layer. With each layer, CNN increases in its complexity, identifying greater portions of the image. Previous layers focus on simple features, such as colors and edges. As the image data progresses through the layers of the CNN, it starts to recognize

larger elements or shapes of the object until it finally identifies the intended object (IBM, n.d.b).

Systems are available to improve the efficiency of labeling images for proper identification of the item. IBM Maximo is such a system. To provide the highest accuracy of identifying an image, many similar images can be used to improve the probability of properly identifying the image. The capturing of the data (images) is time consuming and needs to be done for any item that is expected to be properly identified using CV. Algorithms can be adjusted to focus only on the items that are matching the labeled image as to reduce clutter (abstraction) from objects within the scene. An example of how an image is deconstructed with a CNN is displayed in Figure 15.

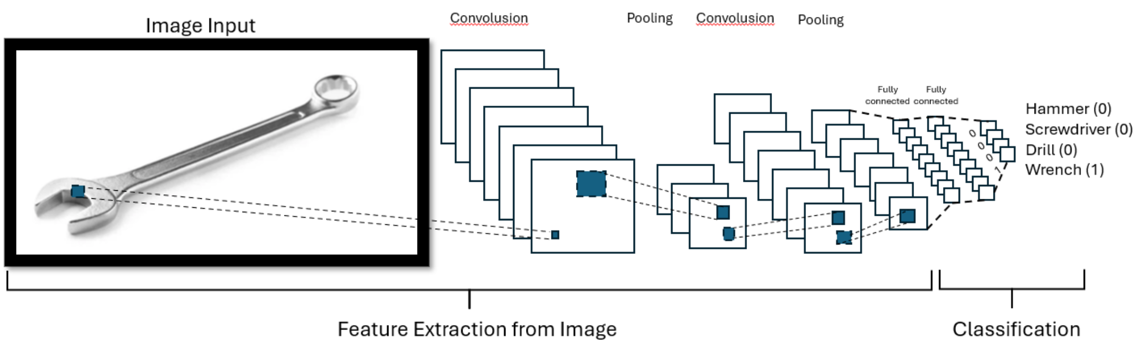

Figure 15. Convolutional Neural Network Example with Input from an Image of a Wrench. Assignment of Weighted Values to Areas of the Image Allows the Calculation of Probability to Determine Identification of the Image.

2. Data Labeling

Data labeling is necessary to ensure there are methods of identification for CV to accurately identify the objects in view. The raw image, video, or audio file is captured. Once captured, a specimen is labeled by a human to assist the computer with learning what is viewed or heard. A label can be as broad as a "yes" or "no" when answering a question such as, is this a wrench? When referencing the image in Figure 15, the answer would be "yes." A data label can be as detailed as describing individual pixels. The data labels are then grouped in layers for reference.

In Figure 16, the 94 second video recording at the bottom captures the actions taken in the video and the list above the recording reflects the labels that identify the action in the respective portion of the video. Data labeling is the foundation for machine learning and deep learning use cases, like CV (IBM, n.d.a). Data labeling requires human input initially. More data supports the more advanced human-in-the-loop participation (IBM, n.d.c). Human-in-the-loop participation typically assists automated data labeling and is a faster way than simply human-only labeling. The participation of humans applies the human's judgment to accurately identify and properly label the image, video, or audio. Human judgment results in applying bias to the data which may produce undesirable outcomes. Establishing standards for labeling practices can assist with reducing human bias.

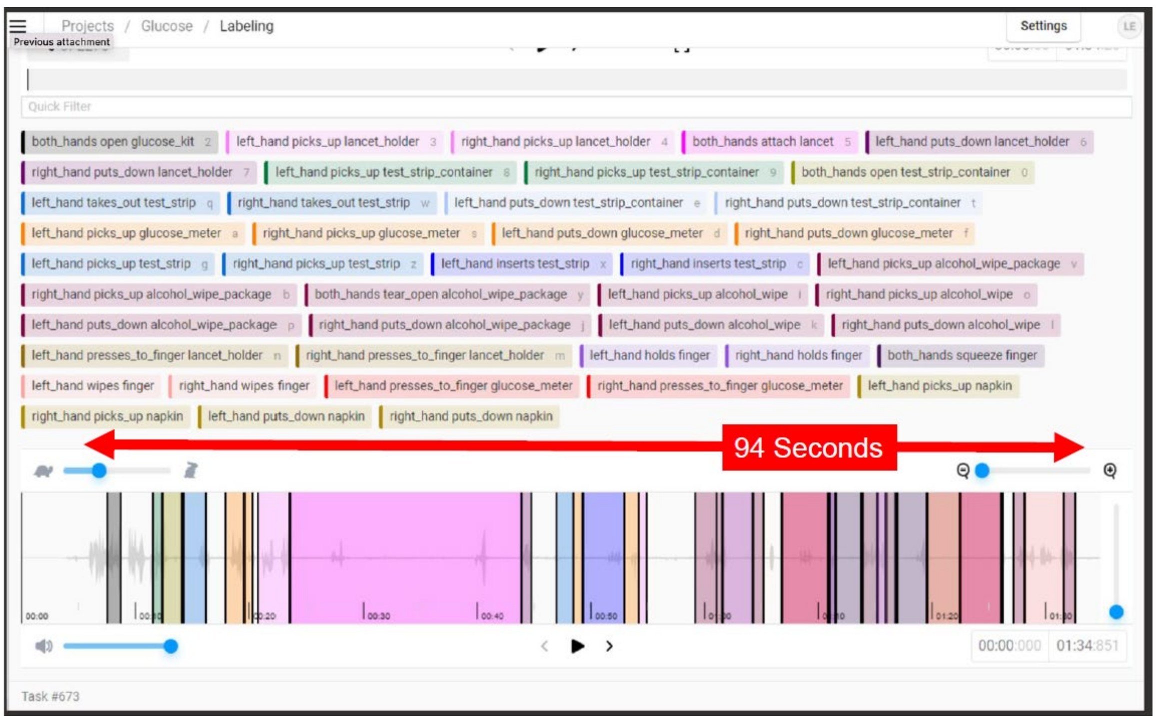

Figure 16. Data Labels of Recorded Video that Show Actions Taken for Conducting a Glucose Test. Source: Raytheon BBN (2023).

Algorithms that use data labels allow the machine to identify anything where training by data labels is applied. Examples include, but are not limited to, faces, objects, buildings, vehicles, and signs. A range of sensor data is available for the application of data labels. Sensors can provide structured or unstructured data. "Unstructured data is data that is not structured via predefined schemas and includes things like images, videos, LiDAR, Radar, some text data, and audio data" (Scale, n.d.).

When labeling an image for CV use, a bounding box is applied. The bounding box is defined by the data labeler and is typically applied tight around the object to improve the accuracy of the label. Figure 17 depicts bounding boxes used to label vehicles. Other methods of applying labels include classification for entire images, cuboids for 3D images, 3D sensor fusion when multiple sensors define an image, lines, ellipses, points, polygons, segmentation, multi-modal, and synthetic data (Scale, n.d.). Bounding boxes can be seen in Figure 17 and are highlighted in green. 3D detection of objects by LiDAR can be seen in Figure 18.

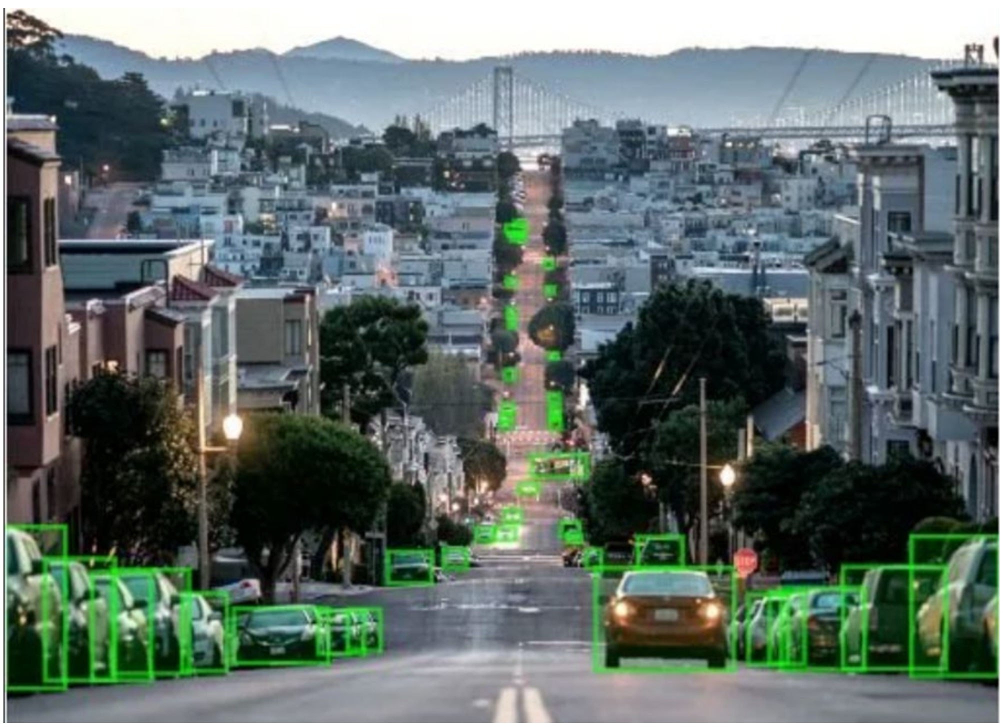

Figure 17. Bounding Boxes Seen Around the Cars in the Image of a Street in San Francisco, California. Source: Scale (n.d.).

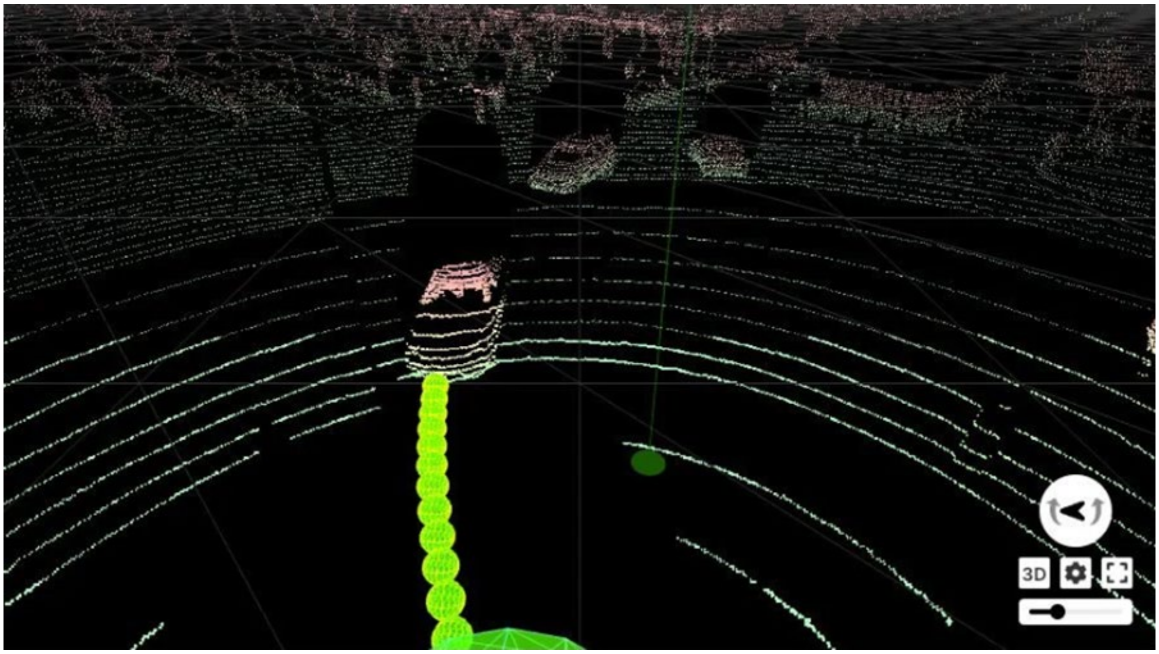

Figure 18. LiDAR Image of a Vehicle Displaying the Ability to Capture a 3D Depiction of the Image. Source: Scale (n.d.).

Appropriate software is required to apply data labels but there are several methods. The first is with an in-house team. This method uses a group of individuals assigned to apply labels to raw data collected and consolidated by the team within the organization (Scale, n.d.). The benefit of an in-house team is control. The second method of labeling is crowd sourcing. The benefit of crowd sourcing is that labels are applied by a larger group of people and can create a larger database of labels. Crowd sourcing is faster but can cause errors in the labels due to a lack of standardization. The third method of labeling is done by a third-party data labeling partner. The third method requires individuals that are certified to handle sensitive information when creating labels for systems that operate in a secure environment. The third method is more costly but can increase the quality of the labels by using teams that are expressly trained and have the technical expertise to conduct the job (Scale, n.d.).

3. Constraints of Computer Vision

CV relies on sensors to observe the environment and relies on the accuracy of the labels applied to the data to identify the objects within view. Without accurate labels, the object in view is not recognized by the machine. The clutter of the image can also prevent the machine from accurately identifying the object, even if a data label exists. This is particularly relevant in environments that are dynamic and have objects that are rapidly changing shape. There are two kinds of environments that help to describe where the limitations of CV are commonly demonstrated: the kind environment and the unkind environment. Kind and unkind environments in the application of CV have not been formally defined and are a concept theorized by the author. The foundation of kind and unkind environments has its roots in psychology and are presented by David Epstein's explanation of learning environments in his book titled, *Range: Why Generalists Triumph in a Specialized World* (Epstein, D., 2019). The author intends to do additional research to better define the terms for further research on military applications of CV. Kind and unkind environments apply to CV.

a. Kind Environment

Kind environments are static, organized, and often contain well defined patterns. The controlled nature of kind environments improves probability calculations and assists with providing consistent raw data that matches variables found within the labeling architecture. Kind environments are found when conducting maintenance or building items on an assembly line where standard repetitive movements and actions occur. Kind environments can also be found in locations where objects do not move, such as buildings or parked vehicles on a street.

b. Unkind Environment

Unkind environments are dynamic, complex, and circumstantial; the object in view may change shape, texture, pattern, or form. Identifying the object in an unkind environment is complicated by the changing nature of the object within view. Unkind environments may be found when objects are moved out of view for a duration of time. Unkind environments may have actions occurring simultaneously. When actions are occluded in some way, the CV may not see the action and therefore be unable to apply a label for object recognition.

c. Kind Versus Unkind Environment

While this thesis does not provide demonstrable evidence that supports the results of object recognition with CV in kind versus unkind environments, observation of laboratory results of labeling actions in kind environments and unkind environments display anecdotal evidence that kind environments are superior for object recognition with CV to unkind environments. Further research is needed to better understand the variables that define kind or unkind environments when using CV and methods for mitigating the variables in unkind environments that will produce better CV identification outcomes.

d. Object Occlusion

Sensor position and/or location of the object within view may create object occlusion. Object occlusion is simply when the object is blocked by something that is between the sensor and the object. The inability of the sensor to see the object prevents CV from identifying the object while it is out of view.

Object occlusion is a difficult problem to solve for CV. When a human sees an object and then the object is occluded, the human maintains short term memory to assist with providing the human with an understanding of what is occurring even if the object is suddenly unseen. Schema assists the human with understanding what is occurring, even when the object is removed from view. CV does not have this cognitive ability and will simply not identify the object when the object is no longer in the field of view.

Conducting maintenance can illustrate an example of occlusion. When someone is conducting maintenance on an engine and they need to remove a bolt that is behind the engine, on the opposite side away from the sensor, the machine is unable to see the bolt. Object occlusion complicates task guidance solutions provided by PTG technology. PTG needs to see the bolt to determine the state of the bolt to provide task guidance. Without seeing the bolt, a solution that provides task guidance is required to be controlled manually. The user has to indicate the task is complete by manually selecting task completion for removal of the bolt, because the sensor or camera was unable to see the bolt removal.

4. PTG Use Cases

The PTG program focuses on four use cases. In TA1 development, various research laboratories used the act of cooking to develop the foundation of the AI data labels and algorithm that supports task guidance. In TA2 development, several commercial laboratories have developed PTG solutions for mechanical maintenance, battlefield medicine, and pilot assistance. While collecting data for this research, the author was only able to collect information from Redshred for the maintenance use case and Raytheon BBN for the combat medicine use case. The identification of cooking tasks for the first use case in TA1 development can be seen in Figure 19.

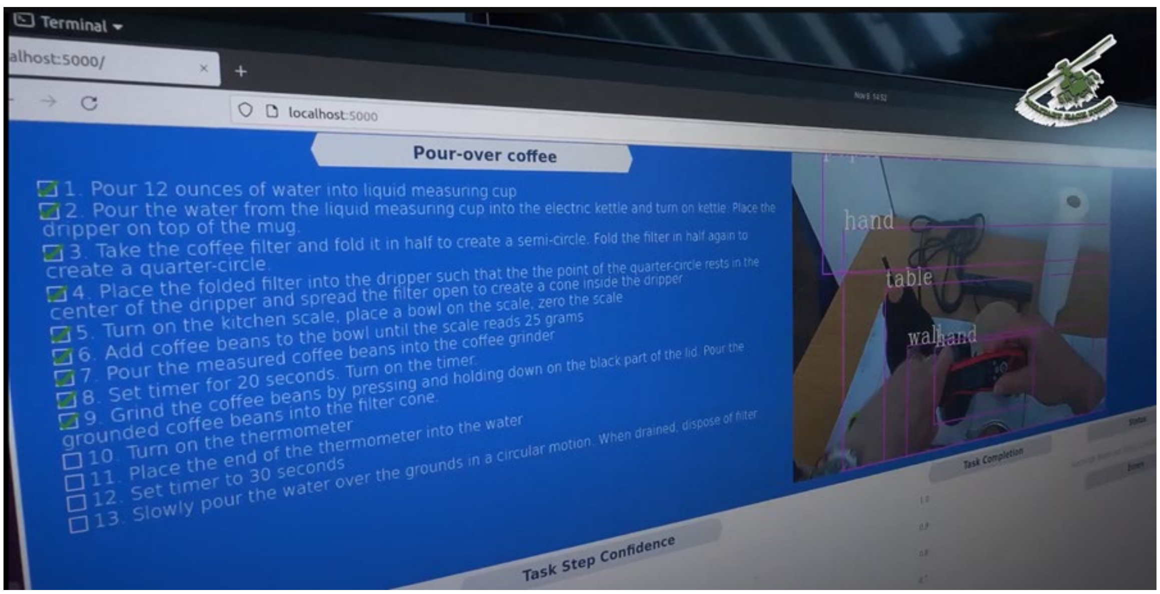

Figure 19. TA1 Developmental Use Case Using the Act of Cooking to Develop PTG. Source: Military Forces TV (2023).

a. Maintenance Use Case

Redshred, a company out of Baltimore, Maryland is participating in the PTG program for TA2 development and has developed a system called COACH. The system focuses on providing task guidance for maintenance actions on a small engine displayed in Figure 20. The proof of concept successfully displays instructions to the user to conduct maintenance actions and provides a foundation for the application of this technology across a broad range of systems.

Figure 20. The Honda Engine Used by Redshred to Develop Maintenance Task Guidance. Source: Redshred (2024).

COACH is accessible by wearing a Microsoft HoloLens 2 headset. The software uses the HoloLens 2 interface for accessing menu selections. A computer provides access to the lines of code for supervision and modification of the code in the laboratory.

Redshred takes advantage of computer aided design (CAD) of the engine to support replicating the engine with a 3D digital image. Redshred uses Unity to create the digital image and constructs the image labels with semantic segmentation. The digital image of the engine can be rotated around the center point of the engine for view from any direction. COACH allows the user to frame the system where they will conduct maintenance. In Figure 21, COACH is displaying the area to map for properly identifying the system. This is displayed with a light blue circle. The user adjusts the size of the circle around the object, the engine in this case, with hand motions. Also displayed is a "Notes" box that provides added information to the user. There is a selection prompt display that allows for the user to manually select the task and manually move the task guidance along to the next task.

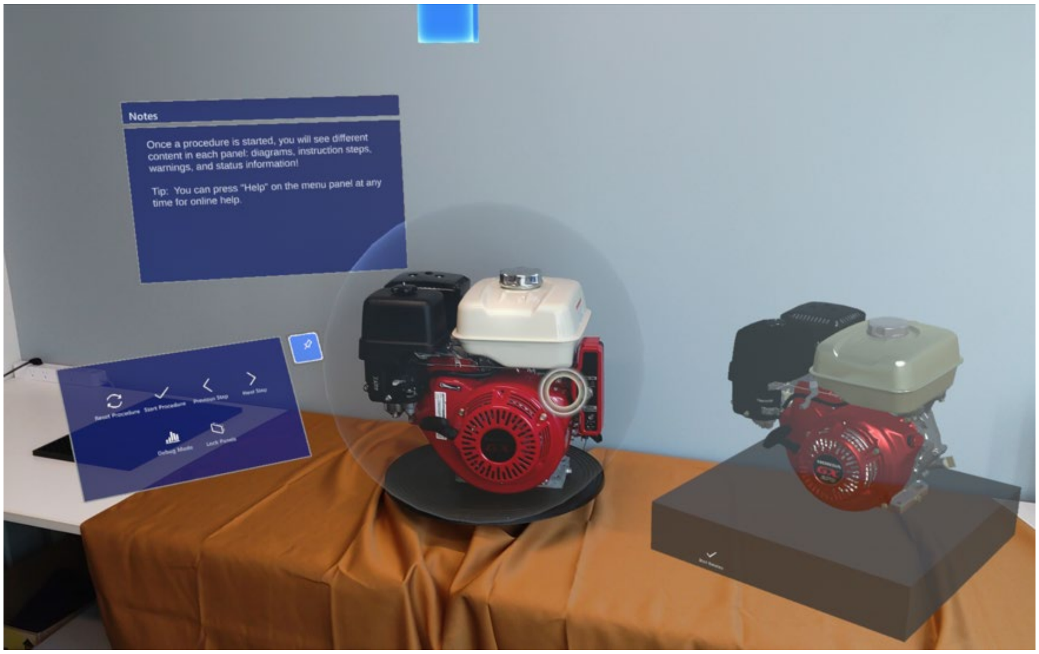

Figure 21. 3D Digital Image of the Small Engine. This Image Rotates with Hand Gestures Tracked by CV. Source: Redshred (2024).

Redshred designed COACH to provide a digital image of the engine for task guidance. COACH also provides audio prompts through the speakers embedded in the HoloLens 2 headset. COACH uses CV to watch the actions that are taken by the user and provides just-in-time guidance by tracking actions. COACH uses a design called "the Orb," displayed in Figure 22, to provide manual and automated access to a sequential task list.

COACH can be modified to provide an abundance of data to the user including information that is traditionally accessible in the Interactive Electronic Technical Manual (IETM) accessed with the PEMA Toughbook. COACH provides a proof of concept for the integration of AI via CV with AR to assist with maintenance actions. This use case has broad application across systems for repair within the Marine Corps.

Figure 22. COACH System Displaying "the Orb" Task List. The Task List Directs the Removal of the Air Filter Cover Nut and Then Shows the Removal of the Air Filter Cover. Source: Redshred (2024).

b. Combat Medicine Use Case

Raytheon BBN is participating in TA2 development in the PTG program to develop the combat medicine use case. MAGIC is a system that uses CV to view the actions that the user is conducting while providing combat medical care and then provides instructions with a menu prompt. Raytheon BBN has identified 50 different tasks to develop task guidance for combat medicine (Raytheon, 2023). Raytheon BBN demonstrated the application of a tourniquet in the Minneapolis, Minnesota laboratory. MAGIC also uses Microsoft's HoloLens 2 head-mounted display as the user interface. Hardware limitations have influenced technology development (Raytheon, 2023). The MAGIC black box is not hardware agnostic. Code would need to be modified to use MAGIC with other AR/XR systems. Tasks for the application of the tourniquet are displayed in Figure 23. The tasks are sequential and are tracked automatically with the CV AI. The user can select an option for multiple casualties and apply various tasks to each of the patients.

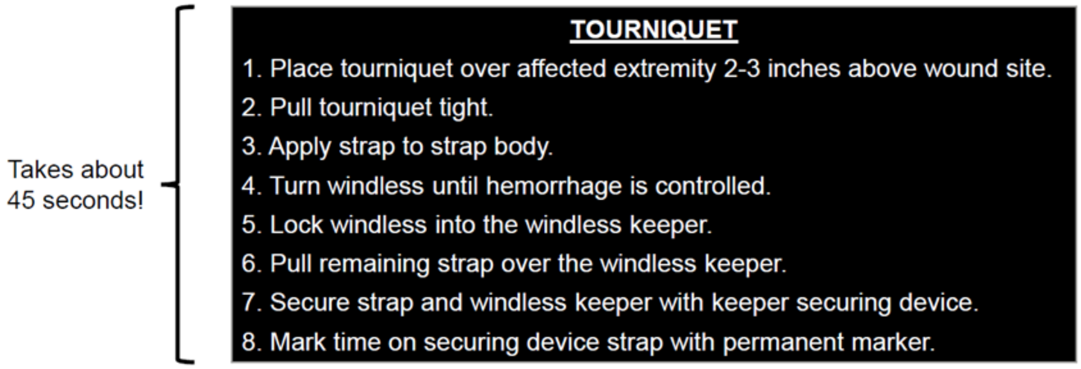

Figure 23. Task Steps Identified With the MAGIC System for Applying a Tourniquet. Source: Raytheon BBN (2023).

MAGIC provides a carousel menu of each task that is displayed above the user. The task carousel is disassociated from the patient to prevent obstruction of view for the user but the information is always available to the user. Tasks are automatically tracked by the AI. The task guidance is hands free, and the CV tracks the completion of each task and then moves to the next sequential instruction upon completion of the previous task.

MAGIC seeks to provide the service member with detailed instructions to assist with improving the probability of casualty survival with the absence of the golden hour (see Figure 24). Combat medicine is a difficult task for CV and is conducted in an environment where the user is pressed for time. The added stress the user is feeling combined with a complex and dynamic scene complicates the ability of the machine to identify the actions with associated data labels. The dynamic nature of the tasks requires more data to provide better solutions. This is noteworthy when considering which use cases are best supported by PTG.

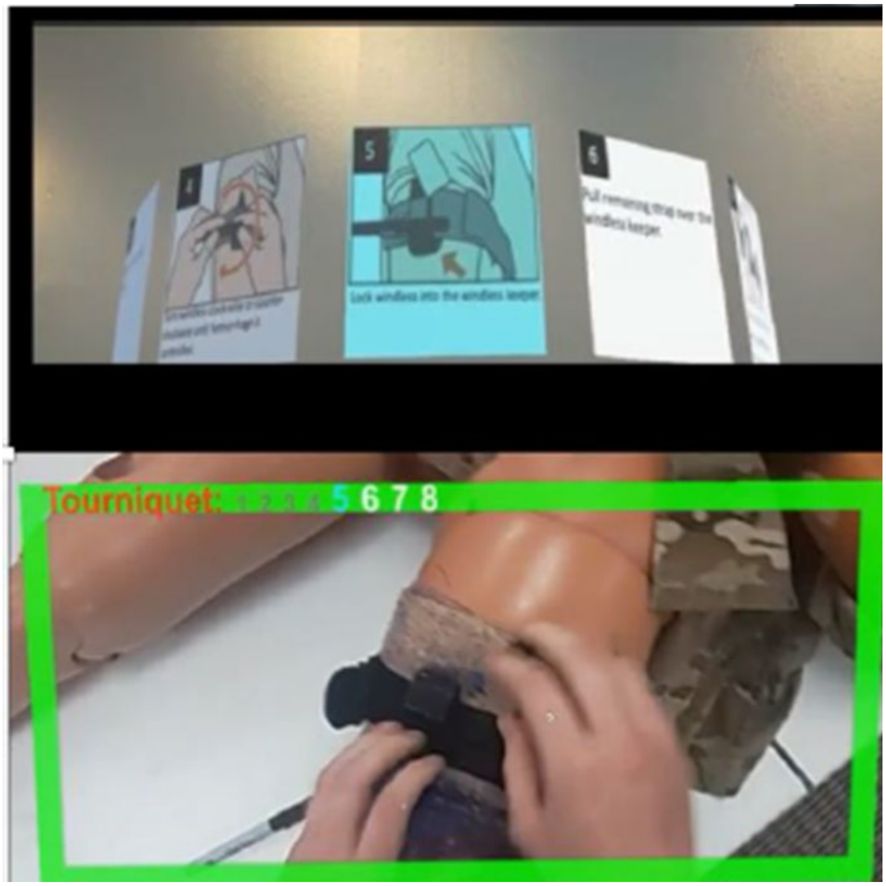

Figure 24. Raytheon BBN MAGIC System Providing Instructions on the Application of a Tourniquet. The Head-Mounted Display Captures the Actions of the User and Guides the User Through Sequential Steps. Source: Raytheon BBN (2023).

J. APPLICATION DEVELOPMENT

1. Agile Software Development

Software development within the Department of Defense has not, until more recently, been a focus of system development. Historically, software development is designed after the system is designed and often after the system is built. Methods of software development include monolithic, waterfall, and agile.

Monolithic software development is a means of developing software where each line of the software code is dependent on the other lines of code. The code is developed for a single system and is hardware dependent. Monolith has one code base and is developed on a closed architecture for a closed system. Integration with a cloud and network infrastructure is difficult with monolithic design and can cause significant errors that affect the entire code infrastructure with a single change of code. Within the DOD, the focus on integration of software across network infrastructure, historically, was not prevalent. Software was developed for a single weapon that supported the function of that single weapon. Additionally, the traditional milestone based, or major capabilities acquisition pathway supports funding and development of single systems. When developing software for those systems, the integration of the software as well as the test and evaluation occur towards the end of the system's development and are unique to the system. Under previous major capabilities acquisition pathways, software development and funding align with testing at the end of product development.

Monolithic software architecture cannot respond quickly to a changing environment. Issues with funding exist with colors of money, allocations of funds from the NDAA for specific spending on programs, and lack of flexibility of funds use. Additionally, monolithic development tends to result in siloed programs that lack integration across networks preventing interoperability. Monolithic software development is slow, because the software code is designed to support the function of a single weapon or system. As per the Atlassian (2024) website, "any changes in the framework or language affects the entire application, making changes often expensive and time-consuming . . . a small change to a monolithic application requires the redeployment of the entire monolith" (Harris, n.d.).

The waterfall method of software development is linear and prescriptive. As a result, waterfall development tends to be a better method of managing timelines, funding, and improves forecasting. Waterfall development is used for complicated, multifaceted projects (Lutkevich et al., n.d.). Waterfall methodology requires upfront prescriptive definitions of requirements. The software is developed per the requirement with little input from the user and, as a result, there is minimal determination if the software is serving the demand of the user. The user is only incorporated into the process at the beginning to assist the engineer with understanding the desired capabilities. The user is then brought back into the development loop during operational testing after the design of the software has already occurred. If the user does not like the result or does not properly meet the requirement, the design process must start at the beginning.

The sequential nature of waterfall development results in siloed development and fosters developmental environments that lack cooperation. Errors in the code are passed off to each sequential team. The design team may not factor in limitations to the code platform. The testing team will find an error and pass the responsibility back to the coding team. The coding team may not fix the code in the way that the end user deems necessary because the user was not consulted in the testing phase of the software development. The coding team then passes the corrected code back to the testing team. The operational phase of the software development may determine that the code works but, in the end, it is software that the user may not want. In this case, the development starts over. According to Ben Lutkevich and Sarah Lewis with TechTarget, waterfall software development does not consider changing requirements or scope and developmental processes do not overlap for simultaneous development (Lutkevich, n.d.).

Agile software development is iterative and includes the end user from the beginning to the end of the development life cycle. The Agile mindset recognizes that small wins add up over time. The iterative feedback loop provides faster development for higher value to the user. *Agile 101* published by the Office of the Under Secretary of Defense for Acquisition and Sustainment (OUSD [A&S]) states, "Agile development life cycle promotes continuous delivery of small increments of working product, which provides opportunities for demonstration to users and capture of near real-time feedback within each delivery cycle." (OUSD, 2023, p. 9) Agile development enables lower initial costs and can reduce the risk of high cost and low value that is not discovered until the end of development. Agile is more flexible and resilient. Agile development empowers teams to be creative and develop solutions that are novel. Agile development provides more opportunities to review the software which improves the quality of the delivered product to the end user. A graphical depiction of waterfall and agile software development is depicted in Figure 25.

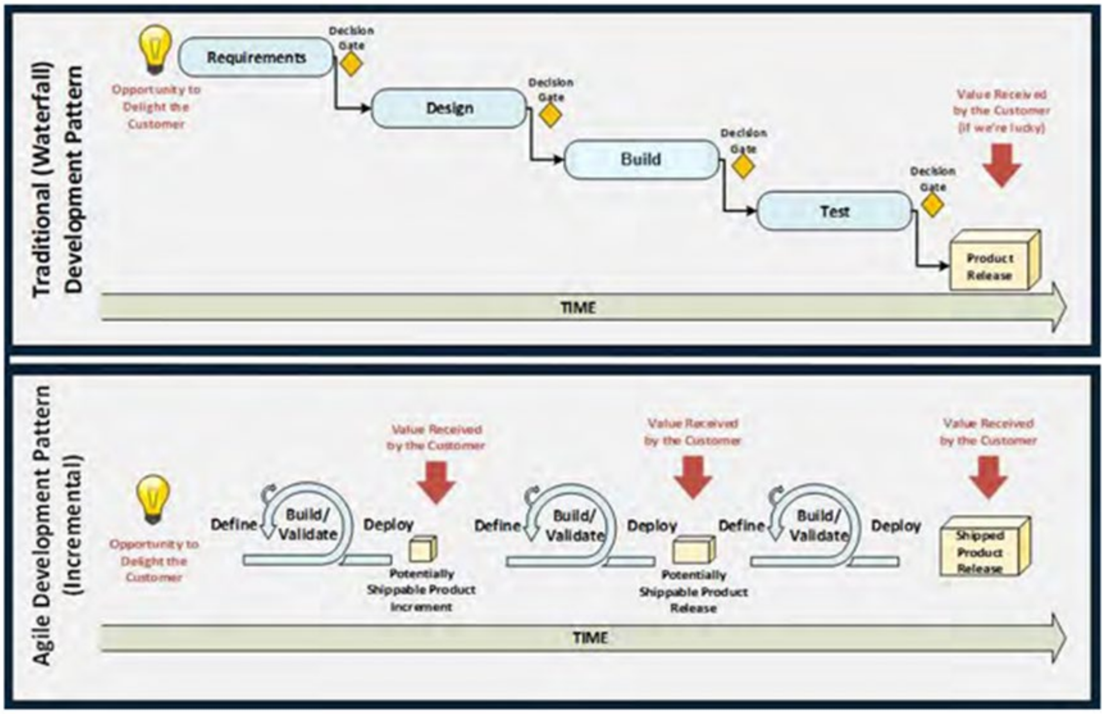

Figure 25. Waterfall versus agile development cycle. Source: OUSD (A&S)

Agile 101 states that with agile development, "the government is responsible for the vision, roadmap, and prioritization of agile backlog requirements, and must work with the contractor to ensure that the desired value is delivered" (OUSD, 2023, p. 10). The government is required to participate in the agile process and include the end user in the development process. Agile development is conducive to supporting development, security, and operations (DevSecOps).

2. Software Containers

Producing various capabilities by modifying software with software containers reduces the time it takes to deliver the product to the user. Everything needed to develop and deploy an application is available in a software container. Software containers support the development and operation of multiple applications. A container supports a common host operating system and infrastructure where modifications in the code can be made in an isolated, secure, and standalone package of software (Docker, n.d.). Containers can support the development of various use cases for PTG.

Software containers prevent issues with moving software from one computing platform to another. The container ensures that the software runs the same by providing a uniform runtime environment (Rubens, 2017). The container supports the application by providing all the "dependencies, libraries and other binaries, and configuration files needed to run it" (Rubens, 2017). The container can provide uniform access to data labels for CV applications, even when stored in the cloud. A single server can host more containers than virtual machines because the storage size of the application in a container is smaller than the storage size of the application on a virtual machine. Applications are accessed faster with containers since containers are always running as compared to a virtual machine which must be booted before you can access the software stored on the machine. Using software containers enable faster support when switching between applications.

Containers support microservices which are individual modules of code that can be modified without changing the entire software application. Modifying application capabilities with microservices prevents the entire software architecture from failing and allows for the software to continue to run while the module is under modification. Microservices and containers support the Marine Corps' ability to establish and maintain software factories.

3. Software Factories

Software factories enable sustainment of software over the life cycle of the software application. A software factory is a group of engineers, users, and code writers that create, modify, and maintain software. Software factories in the DOD support DevSecOps and can take advantage of software containers to reduce the impact of code modification across the greater software application.

A software factory can assist with modification of applications that are developed by a prime contractor. The prime contractor can develop the minimal viable product (MVP). Once the MVP is delivered, the software factory can modify the application to improve the software capability and customize the product to provide varying capabilities as the user asks for additional capabilities. The software factory can support data labeling for CV. The data collection for CV and applying labels can be labor intensive. A software factory can support reducing costs for the continued development of the MVP.

CONCLUSIONS

K. CONCLUSIONS AND RECOMMENDATIONS

1. Perceptually Enabled Task Guidance

DARPA is coordinating the development of PTG for various use cases with military applications. PTG uses CV technology to assist with the conduct of tasks and can be modified to support a range of use cases. While CV, AI, and AR//VR/XR platforms are not new technologies, the combination of these technologies envisioned by Dr. Bruce Draper, DARPA Program Manager for PTG, is solving a variety of complex problems. In accordance with the research proposal submitted by I MEF, PTG provides an opportunity for further research to improve current PTG technology to assist Marines with just-in-time task guidance in distributed, austere environments where Marines are required to complete complex tasks with minimal support. It is recommended that the Marine Corps work with DARPA on ways to participate in this research and fund future development of applications for various use cases within the Marine Corps.

PTG technology has not matured and is still in TA2 and initial development stages. PTG requires additional funding for future application development. The PTG program would benefit from user input from across a variety of military communities. The Marine Innovation Unit and the Marine Corps Warfighting Laboratory are positioned to assist DARPA with further PTG development and participation in TA3 evaluation of the three military use case applications: mechanical maintenance, combat medicine, and pilot assistance.

PTG requires data labeling, a labor-intensive task. Internal data labeling teams within the Marine Corps can achieve the data collection and labeling required for PTG applications. Crowd sourcing data collection is another option. Crowd sourcing data collection poses increased risk with the quality of the data and presents a challenge with the process of labeling the data. Crowd sourcing data collection would reduce the time needed to implement additional applications for PTG technology but may not provide adequate quality needed for optimal performance.

The adoption of a common operating system for the use of PTG technology would assist with reducing the limitations of siloes imposed by single operating systems that run on unique hardware. Hardware agnostic operating systems, such as Meta's Horizon OS, will support multiple hardware devices that can be modified to run on the common operating system. The Marine Corps should consider a common operating system that supports integrating multiple AR/VR/XR systems.

PTG provides mechanisms for hand and arm tracking through CV but poses the problem of object occlusion and complications of object or action recognition with the distortion of the object in view. Distortion in complex, unkind environments coupled with object occlusion creates a problem for CV. Thus far, research laboratories use Microsoft HoloLens 2 for PTG development. It is recommended that PTG technology continue development with more complex and advanced AR/XR hardware such as Microsoft IVAS or Meta Quest 3. Using more advanced AR/XR hardware platforms may assist with reducing the risks imposed by object occlusion and distortion. The geographic location of where the hardware systems are manufactured should be factored when desiring to use these systems in sensitive, confidential environments.

The use of camera suites can also assist with object occlusion. Rather than have a single set of cameras providing CV from a head-mounted display, a suite of cameras placed around an object may assist with providing the identification of actions and objects that otherwise would not be seen from a single point of view.

Large language models (LLM) can improve the quality of the PTG product. Raytheon BBN suggests that LLM can facilitate automation of functions, such as the drafting of a report like a casualty evacuation nine-line report or maintenance action form. LLM can assist the user with providing better information and user provided prompts to the LLM would support extracting specific and detailed information requested by the user.

Additional AR concepts that may benefit PTG development include eye gaze selection. Eye gaze selection would allow a hands-free method of data selection or manual task guidance selection while the user's hands are busy conducting the task. An additional AR concept that may improve PTG is remembering where objects are located.

Remembering where an object is located benefits Marines working with many different tools. A Marine could simply ask the AI assistant for the location of a specific tool and the assistant would tell the Marine where it was last seen.

2. Software Factories

PTG application development requires continual modification of software. Data labeling will be ongoing during application development and application sustainment. It is recommended that the Marine Corps seek out additional companies for future PTG application development.

As PTG technology matures, it is recommended the Marine Corps contract with prime manufacturers to develop a MVP unique to specific use cases. Buying PTG applications is unlike buying a piece of hardware in the sense that it is software specific, requires continual maintenance and sustainment of software code, as well as code modification. A software factory supports these requirements. It is also recommended that the Marine Corps partner with the prime manufacturer by contracting embedded software engineers from the prime that are subject matter experts in the development of the MVP to support with the complexities of modifying, sustaining, and maintaining the code.

Software containers would support uniform development of PTG applications and allow for software factories to modify modules of software, not alter the entire application, and prevent a complete overhaul of the application.

L. FUTURE WORK

1. Survey Military Users

The Marine Corps should conduct surveys of Marines across a variety of communities to better understand the needs of Marines regarding task guidance. The Marine Corps should survey communities about what would be needed to conduct a specific task where they are unfamiliar with the process. Marines should be consulted on conducting tasks that are not unique to the military occupational specialty that they have already been trained to perform.

2. Cyber Security for the Development of AR/VR/XR Systems

DARPA Program Manager Matthew Wilding is working on Intrinsic Cognitive Security which aims to identify methods of providing cyber security for AR/VR/XR platforms. Future research in security operations within the metaverse and while using AR/VR/XR platforms is needed as these systems are increasingly used in operational environments.

3. Kind Versus Unkind Environments for Computer Vision

Further development of the theory of kind and unkind environments will assist with better understanding which use cases are more conducive to CV applications within the Marine Corps and across the DOD.

M. SUMMARY

PTG advances the ability to use AR/XR platforms not only in training, but also in operational environments. As the Marine Corps moves to conducting more distributed operations where fewer Marines are expected to perform more tasks, digital task guidance can assist in expanding the skills needed for Marines to perform a wider range of tasks.

The research in this thesis identified AR/VR/XR systems developed commercially and through military research laboratories that have the kind of technology that supports the integration of PTG technology. As PTG technology matures, a greater number of applications will support more tasks for military applications.

CV provides methods for identifying actions, hand and arm tracking, and task guidance. CV has its limitations and as PTG continues to improve, methods of mitigating those limitations will follow. The Marine Corps would benefit from investing in PTG technology as it aligns with Marine Corps Force Design concepts and is a natural fit in the Project Tripoli portfolio.

LIST OF REFERENCES

Beinert, M. (2022). Army gets $360 million IVAS procurement cut, $300 million ENVG-B increase in final FY ‘23 budget. *Defense Daily*. https://www.defensedaily.com/army-gets-360-million-ivas-procurement-cut-300-million-envg-b-increase-in-final-fy-23-budget/army/

Blanchard, O. (2021). *Why Microsoft’s $21 Billion IVAS Contract with The U.S. Army is a Much Bigger Deal Than Meets the Eye*. TheFuturm Group. https://futurumgroup.com/insights/microsofts-21-billion-ivas-xr-contract-with-the-u-s-army/

Brown, G., Baillot, Y., Bailey, M., Pfluger, K., Maassel, P., Thomas, J., Julier S. (2005). Using Augmented Reality to Enhance Fire Support Team Training [Research Report]. *Interservice/Industry Training, Simulation, and Education Conference 2005*.

Center for Naval Analysis. (2021). *AI Considerations for the Marine Corps.*

Defense Advanced Research Projects Agency. (2021, March 5). *Broad Agency Announcement perceptually-enabled task guidance (PTG)*.

Department of Defense [DOD]. (2017, May). RDT&E Budget Item Justification: FY 2018 Navy.

Department of Defense [DOD]. (2022, June). *U.S. Department of Defense responsible artificial intelligence strategy and implantation pathway*.

Department of Defense [DOD]. (2023). *National defense science and technology strategy 2023*.

Dixon, L. J. (2022, September). *Shipboard 3-M program supplemented by AR technology* [Master’s Thesis, Naval Postgraduate School]. NPS Archive: Calhoun. https://calhoun.nps.edu/server/api/core/bitstreams/8a8e49ee-3f86-4afd-a616-f9f05f6dc293/content

Docker. (n.d.). *What is a Container?*. Retrieved on May 6, 2024, from https://docs.docker.com/guides/walkthroughs/what-is-a-container/#:~:text=A%20container%20is%20an%20isolated,to%20a%20base%20operating%20system.

Duffie Jr, W. (2021, April 9). *Office on naval research tests virtual training systems for JTACs, fire support Marines*. Office of Naval Research.

Dunford, J., (2015). 36th Commandant’s Planning Guidance. United States Marine Corps.

Epstein, D. (2019). *Range: Why Generalists Triumph in a Specialized World*. New York, Riverhead Books.

Etemadi, A., & Kamp, J. (2022, May 13). *Built for speed: The Army's integrated visual augmentation system (IVAS): A middle tier acquisition case study* [Case Study, Acquisition Research Program]. NPS Archive. Calhoun: https://calhoun.nps.edu/server/api/core/bitstreams/12859b74-b294-49aa-8e0b-c788cefa8592/content

Feiner, S., MacIntyre, B., Höllerer, T. & Webster, A. (1997). A touring machine: Prototyping 3D mobile augmented reality systems for exploring the urban environment. *Personal Technologies 1*, 208–217. https://doi.org/10.1007/BF01682023

Federal Procurement Data System. (2018). Microsoft Corporation Transaction Description. https://www.fpds.gov/common/jsp/LaunchWebPage.jsp?command=execute&requestid=176797495&version=1.5

Federal Procurement Data System. (2019). Microsoft Corporation Transaction Description. https://www.fpds.gov/common/jsp/LaunchWebPage.jsp?command=execute&requestid=176797673&version=1.5

Harper, J. (2023). *Army awards Microsoft $95 Million for additional IVAS 1.2 headsets, virtual trainers*. Defense Scoop. https://defensescoop.com/2023/09/21/army-awards-microsoft-95m-for-additional-ivas-1-2-headsets-virtual-trainers/

Harris, C. (n.d.). *Microservices vs. Monolithic Architecture*. Retrieved on May 4, 2024, from https://www.atlassian.com/microservices/microservices-architecture/microservices-vs-monolith

HAVIK. (n.d.). *HAVIK Core*. https://www.havik.us/havik-coretrade

IBM. (n.d.a). *What is computer vision?*. Retrieved May 5, 2024, from https://www.ibm.com/topics/computer-vision

IBM. (n.d.b). *What are convolutional neural networks?*. Retrieved May 6, 2024, from https://www.ibm.com/topics/convolutional-neural-networks

IBM. (n.d.c). *What is data labeling?*. Retrieved May 6, 2024, from https://www.ibm.com/topics/data-labeling

Kemmerer. K. E. (2008). Tactical Decision Making Under Categorical Uncertainty with Applications to Modeling and Simulation [Master's thesis, Naval Postgraduate School]. NPS Archive: Calhoun. https://calhoun.nps.edu/server/api/core/bitstreams/cc335808-e741-41fe-b4b1-c56335ec28db/content

Lutkevich, B., Lewis, S. (n.d.). *What is the Waterfall Model?*. Retrieved on May 6, 2024, from https://www.techtarget.com/searchsoftwarequality/definition/waterfall-model

Marge, M. (2023). *Perceptually enabled task guidance*. Defense Advanced Research Projects Agency. https://www.darpa.mil/program/perceptually-enabled-task-guidance#:~:text=The%20Perceptually-enabled%20Task%20Guidance%20%28PTG%29%20program%20aims%20to,skillset%20and%20more%20proficient%20by%20reducing%20their%20errors.ually-enabled Task Guidance

Meta. (n.d.). *Meta Quest 3*. Retrieved May 2, 2024, from https://www.meta.com/quest/quest-3/

Military Forces TV. (2023, April 10). *Revolutionizing Military Training with DARPA AI-Powered PTG Program* [Video]. https://www.youtube.com/watch?v=YjmIIj2QGPM

Mills, B., (2014). *Live, Virtual, Constructive-Training Environment: A Vision and Strategy for the Marine Corps* [Applied Research Report, Naval Postgraduate School]. NPS Archive: Calhoun. https://calhoun.nps.edu/server/api/core/bitstreams/6bc6209b-82f0-40c6-91b9-2fc9dbee3745/content

Mustapha, S., Chong, C. A., & Mohammed, M. N., (2021, December 10–11). Review of the usage of mixed reality and augmented reality assisted learning tool in aircraft maintenance. *2021 IEEE 9th Conference on Systems Process and Control*. (168–173).

Office of the Under Secretary of Defense for Acquisition and Sustainment. (2023). *Agile 101: An agile primer*.

Office of Naval Research. (2022, September 20). *Office of Naval Research The JTAC augmented reality training systems* [Video]. https://www.youtube.com/watch?v=LjJm9EGSBzItube.com

Office of Naval Research. (2023). *Tactical AI for Marine Corps*.

One Network Enterprise. (n.d.). *What is NOSS?*. Retrieved May 20, 2024, from https://www.onenetwork.com/supply-chain-management-resources/supply-chain-glossary/what-is-noss/#:~:text=NOSS%20stands%20for%20%22Naval%20Operational,Expeditionary%20and%20Shore%20Support%20Units.

Qualcomm. (2024). Snapdragon XR2 gen 2 platform. [Performance stats sheet]. https://docs.qualcomm.com/bundle/publicresource/87-73689-1_REV_A_Snapdragon_XR2_Gen_2_Platform_Product_Brief.pdf

Raytheon BBN. (2023, September 15). *PTG MAGIC* [PowerPoint Slide Deck].

Redshred. (2024). *Images of COACH* [Photographs].

Rosenblum, L., Feiner, S., Julier, S., Swan II, J., & Livingston, M. (2012). *The development of mobile augmented reality* [Report]. Naval Research Laboratory.

Rubens, P. (2017, June 27). *What are Containers and Why do You Need Them?*. CIO. https://www.cio.com/article/247005/what-are-containers-and-why-do-you-need-them.html

Sanders, J., Vogel, A., & Rogers, J., (2018, December). *How can the Center for Navy Security Forces leverage immersive technologies to enhance its current training* [Master's Thesis, Naval Postgraduate School]. NPS Archive. Calhoun. https://calhoun.nps.edu/server/api/core/bitstreams/a20b2c3d-7be2-4a1d-a626-affd01778b63/content

Scale. (n.d.). Data labeling: *The authoritative guide*. Retrieved May 6, 2024, from https://scale.com/guides/data-labeling-annotation-guide.

S&P Global. (2023, August). *2023 global trends in AI report*. https://www.weka.io/resources/analyst-report/2023-global-trends-in-ai/#:~:text=The%202023%20Global%20Trends%20in%20AI%20Report%20reflects%20a%20mix,this%20influx%20of%20AI%20innovation

Toledo, J., Martinez, J. J., Garrigos, R., & Ferrandez, J. M., (2010). *Design of embedded augmented reality systems*. IntechOpen.

Training and Education Command. (2014a, July 17). *Concept of operations (CONOPS) for the United States Marine Corps live, virtual, and constructive—training environment (LVC-TE)*.

Training and Education Command. (2014b). MAGTF training and education operational advisory group [Presentation].

Training and Education Command. (2023). *Project Tripoli Overview* [PowerPoint Slides].

United States Air Force. (n.d*.). Combined air operations central*. U.S. Air Forces Central. https://www.afcent.af.mil/About/Fact-Sheets/Display/Article/217803/combined-air-operations-center-caoc/

United States Marine Corps [USMC]. (2023, January). *Training and education 2030*. https://www.marines.mil/Portals/1/Docs/Training%20and%20Education%202030.pdf

United States Marine Corps [USMC]. (n.d.). *Project Tripoli*. Retrieved April 22, 2024, from https://www.tecom.marines.mil/Initiatives/Project-Tripoli

Wagoner, N. D., & Satanek, R. A., (2021*). Virtual reality ground force commander trainer* [Master's Thesis, Naval Postgraduate School]. NPS Archive: Calhoun. https://calhoun.nps.edu/server/api/core/bitstreams/c7be7f2f-a88e-4c52-8f30-7592cf2f4361/content

Xiphos Partners. (n.d.). *JVT overview*. Retrieved April 22, 2024, from https://xiphos.partners/

Acquisition Research Program
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net