NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE REPORT

OPERATIONAL ANALYSIS FOR OFFENSIVE MINE WARFARE

by

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June 2020

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE June 2020	3. REPORT TYPE AND DATES COVERED Systems Engineering Capstone Report

4. TITLE AND SUBTITLE
OPERATIONAL ANALYSIS FOR OFFENSIVE MINE WARFARE

5. FUNDING NUMBERS

6. AUTHOR(S) Christopher R. Desanto, Jenna L. Drummond, Russell A. Helger Jr., Ryan P. Mcdonough, and David Perry

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

Offensive mine warfare (OMW) is an often overlooked and underdeveloped potential benefit to the breadth of options available for current naval forces regarding enemy deterrence. By taking a modified systems engineering Vee approach and applying it to offensive mine warfare, this project provides a definition of existing operational concepts and projects the future potential of this methodology. This project defines two simulations utilizing OMW in both an open-ocean transit mission and an ocean strait escort mission. These mission scenarios help provide the composition of the interconnected system of systems involved with the deployment, loiter, engagement, and recovery functions of offensive mines. An emphasis is placed on the use of Advanced Undersea Weapons Systems to carry out these functions, specifically large-displacement unmanned underwater vehicles. Simulations provided within this project better map the interconnection of the deployment, loiter, engagement, and recovery functions as they pertain to the measures of effectiveness for each mission scenario. By decomposing the major functions of OMW, this project provides the initial framework for the inclusion of offensive mining into the current naval forces' repertoire of enemy-deterrence options. Additionally, this project's decomposition of offensive mining in its current iteration provides the framework for a further investigation into the future capabilities of this product.

14. SUBJECT TERMS
offensive mine warfare, OMW, mines, unmanned underwater vehicles, unmanned aerial vehicles, deterrence, operational concept, measures of effectiveness, deployment, loiter, engagement, recovery

15. NUMBER OF PAGES
85

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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OPERATIONAL ANALYSIS FOR OFFENSIVE MINE WARFARE

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 2020

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ABSTRACT

Offensive mine warfare (OMW) is an often overlooked and underdeveloped potential benefit to the breadth of options available for current naval forces regarding enemy deterrence. By taking a modified systems engineering Vee approach and applying it to offensive mine warfare, this project provides a definition of existing operational concepts and projects the future potential of this methodology. This project defines two simulations utilizing OMW in both an open-ocean transit mission and an ocean strait escort mission. These mission scenarios help provide the composition of the interconnected system of systems involved with the deployment, loiter, engagement, and recovery functions of offensive mines. An emphasis is placed on the use of Advanced Undersea Weapons Systems to carry out these functions, specifically large-displacement unmanned underwater vehicles. Simulations provided within this project better map the interconnection of the deployment, loiter, engagement, and recovery functions as they pertain to the measures of effectiveness for each mission scenario. By decomposing the major functions of OMW, this project provides the initial framework for the inclusion of offensive mining into the current naval forces' repertoire of enemy-deterrence options. Additionally, this project's decomposition of offensive mining in its current iteration provides the framework for a further investigation into the future capabilities of this product.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOI	area of interest
ASuW	anti-surface warfare
ASW	anti-submarine warfare
AUWS	Advanced Undersea Weapons System
BM	battlespace management
C2	command and control
CDM	Clandestine Delivered Mine
CG	guided missile cruiser
COA	course of action
CNO	Chief of Naval Operations
COTS	commercial off-the-shelf
CSF	Commander, Submarine Forces
CSG	carrier strike group
CVN	aircraft carrier
DDG	guided missile destroyer
IO	information operations
ISR	intelligence, surveillance and reconnaissance
JDAM	Joint Direct Attack Munition
LDUUV	large displacement unmanned undersea vehicle
LMW	littoral & mine warfare
MBSE	model-based systems engineering
MCM	mine countermeasures
MK	mark
MOE	measure of effectiveness
MOP	measure of performance
NPS	Naval Postgraduate School
NUWC	Naval Undersea Warfare Center
NSWC	Naval Surface Warfare Center

OAO	offensive attack operations
OMW	offensive mine warfare
ONI	Office of Naval Intelligence
OPNAV	Office of the Chief of Naval Operations
OV	operational view
PEO	Program Executive Office
PEO USC	Program Executive Office Unmanned and Small Combatants
PMS	Program Manager, Ships
ROE	rules of engagement
SLMM	Submarine Launched Mobile Mine
SSN	attack submarine (nuclear propulsion)
TDD	target detection device
UAV	unmanned aerial vehicle
UHF	ultra-high frequency
U.S.	United States
USN	United States Navy
UUV	unmanned undersea vehicle
VHF	very-high frequency
XLUUV	extra-large unmanned undersea vehicle

EXECUTIVE SUMMARY

For decades, the U.S. Navy has focused its mine warfare efforts on avoidance and countermeasures in response to several attacks on naval vessels since the start of the Gulf War. Despite the well-documented effectiveness of mines against U.S. forces, The United States has invested little towards advancing the development of offensive mine warfare. The use of mines as both an offensive and asymmetric force multiplier is an overlooked and underdeveloped potential asset to the current breadth of naval forces. The development of Advanced Undersea Weapons Systems (AUWS), along with the increasing implementation of various unmanned naval systems, are prospective assets that warfare commanders should be investing in as a means to deploy offensive mines in response to the need for battlespace manipulation and control.

This project sought to develop a concept of operations for offensive mines as an asymmetric force multiplier, as well as the associated system requirements and architecture required to operate integrally with current naval systems. In addition, this project simulated the proposed system to determine the aspects of system that have the largest impact on operational effectiveness in real-world environments. This research broadened the knowledge base associated with the utilization of the offensive mine warfare and established an in depth utility analysis of the individual systems within that framework.

The system architecture alternatives described in this report were developed using a combination of current and near-future naval technology, with an emphasis on unmanned integration with current U.S. Naval forces. By incorporating force structures commonly used by current naval forces and unmanned systems similar to those currently in development, the system architectures are a useful reference for future work in regards to offensive mine warfare.

Two scenarios derived from real-world naval operations provided the environment in which the architecture alternatives were developed and simulated. The first scenario describes a strait transit escort mission in which the geographical area is constrained, the amount of neutral shipping is high, and the enemy force consists of a large number of

vessels. In this scenario, an unmanned undersea vehicle is the mine delivery asset and a submarine acts as the command and control platform. The second scenario describes an open-ocean engagement scenario between two strike groups, where the geographical area is much larger, there is less frequent neutral shipping, and the enemy force has fewer ships. In this scenario, an aircraft carrier acts as the command and control asset while unmanned aerial vehicles deploy the minefield.

The system architectures described in the scenarios were modeled using MATLAB to provide analysis of the different alternatives. The analysis was performed with the goal of determining the effect of selected variables on system effectiveness in both operational scenarios. System effectiveness was defined by the time to deploy the minefield and prevention of enemy ships from entering the area of interest. The selected variables for analysis were the delivery asset characteristics, including capacity, number and speed; minefield characteristics including size and number; and the reliability of different assets in the system.

After analysis of the simulation data, several conclusions were drawn about the proposed system. Firstly, in both scenarios, the number of UUVs/UAVs and the capacity of those UUVs/UAVs had a larger impact on system performance than any other variables. Secondly, the system was discovered to be ineffective as a standalone weapon, allowing enemy ships to enter the area of interest in every trial. However, it did deter a significant number of ships, which demonstrates its ability to act as a force multiplier. In addition, the simulation results showed that an offensive mine warfare system would require a significant amount of support in the form of multiple deployment assets and replacement mines to be effective. Finally, the simulation also demonstrated the minefield's limited ability to scale its effectiveness with an increase in size, requiring that the system be constrained and focused in a relatively small geographical area.

ACKNOWLEDGMENTS

The Offensive Mine Warfare (OMW) Team would like to extend a special thanks to Rear Admiral Richard Williams (Retired), Professor Paul Beery, and Professor Eugene Paulo for their extensive knowledge, guidance, support, and constructive feedback during the capstone project. Additionally, the team would like to thank our families, friends, and respective commands and employers who supported our efforts over the last two years and made this achievement possible.

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I. INTRODUCTION

Throughout history, mine warfare has swayed the outcomes of wars dating as far back as 1778 (Edwards and Gallagher 2014). Mine warfare, when used correctly, allows for an asymmetric advantage on the battlefield. American soldiers, which consisted of an ill-equipped army with minimal supplies and training back in 1778, used powder kegs that floated on the water to blockade the powerful British navy in Delaware. Additionally, during World War II, Operation Starvation played a major role in the United States' fight against Japan. Mines laid by B-29s accounted for 1,250,000 tons of Japanese shipping losses over the span of four months. By comparison, submarines accounted for 4,780,000 tons of shipping losses over the span of 44 months.

Over the past 125 years, offensive mining has contributed significantly to the elimination of hostile enemy ships when compared to all other weapon types combined (Edwards and Gallagher 2014). Offensive mining has historically proven to be a successful offensive option to the United States Navy (USN) in regards to offensive deterrence and battle space manipulation. By expounding on the projected benefits of offensive mining as it pertains to enemy deterrence and control, this project aims to emphasize its importance as a key player in battle spaces of the future.

To preserve naval superiority and maneuverability, the USN has invested time and resources towards countermine warfare. The dominant mentality thus far in the 21st century of the USN is mine warfare is primarily that of a defensive effort; the concern is with mine detection and countermeasures. As a result, the USN's offensive mine warfare capabilities are comparatively underdeveloped. The major contributing factor to this lack of development is a lingering ideology that utilizing mines is a practice done by "weaker" and "smaller" navies, thus not receiving as much sponsorship (Winnefeld and Ahmad 2018).

A. OFFENSIVE MINING CHALLENGES

While there is an opportunity to utilize offensive mine warfare as a force multiplier for the USN, there are additional considerations that contribute to the complicated nature of the problem. Three major concerns associated with mine warfare are: 1) the need for

multiple sorties when properly deploying a minefield, 2) mine removal post-conflict requires considerable time and resources and, 3) mines deployed by friendly forces may limit the USN's maneuverability (Edwards and Gallagher 2014). Moreover, confusion over international laws allowing the use of sea mines requires additional investigation. For example, rules of engagement require naval mines be distinguishable between innocent and enemy mines based on the country that deployed them. This data is recorded on land prior to mine deployment in order to hold each country responsible for retrieving the mines they have deployed after they have satisfied their use. Additionally, the how, where, when and why a naval entity intends to use offensive mines also needs to be disclosed internationally as well. One common accepted principle regarding the practice of naval mining states that mines cannot occupy the water of another country, international waters, or territorial seas during peacetime. All of these cumbersome factors have made mine warfare a low priority for the USN (Winnefeld and Ahmad 2018).

Foreign naval operations are expanding in range and complexity at a rate that has revealed how wide some of the United States' capability gaps are. These are capability gaps that expose technological areas that were once undisputed technological titles of the USN that are now seen as inferior (Winnefeld and Ahmad 2018). In 2013, acknowledging the importance of submarines and mines in the control of the undersea domain, the Chief of Naval Operations (CNO) Admiral John Greenert designated the Commander, Submarine Forces (CSF), as the development lead for the undersea domain (Edwards and Gallagher 2014). The CSF at the time, "Vice Admiral Michael Connor implemented his plan to sustain U.S. undersea dominance, one focused on innovation and rapid delivery to the Fleet" (Edwards and Gallagher 2014, para. 5). Admiral Connor emphasized this point stating, "the torpedo of the future and the offensive mine of the future will be hard to distinguish" (Edwards and Gallagher 2014, para. 5). The Admiral's plan "also called for the use of distributed networks, autonomous unmanned underwater vehicles, firepower, stealth, and the ability to 'act quickly with a profound degree of surprise, force, and lethality'" (Edwards and Gallagher 2014, para. 5).

Expanding on the ideas presented in Edwards and Gallagher (2014), the placement of mines was investigated to better understand minefield performance on the initial threat

to a target. To compensate for threat to target relationships, passive detection capabilities are heavily considered in this project's model in order to separate threat classifications (friendly, enemy, and neutral). Taking into account threat to target probabilities, operational diagrams revolving around the deployment, loiter, recovery, and relocation of offensive mines developed for this project are focused on identifying and monitoring mine placement in relation to threat and target locations. The concepts of threat to target, weapon performance and mine placement were also considered when developing the measures of performance and measures of effectiveness for this project.

The USN has investigated multiple avenues to deploy mines in an effective and safe manner without the need for other resources to be at risk. Many of those avenues have led to the development of Unmanned Underwater/Aerial Vehicles (UUVs/UAVs) that have the capability to deliver mines within a network of submarines, surface ships, and other autonomous vehicles. Research has examined three major UUVs as potentially useful in this area: Large Displacement UUVs, Recoverable UUVs, and Expendable UUVs (National Research Council 2005).

Based on the range of analyses that have investigated the operational impact of offensive mining, this report develops an integrated system's architecture that serves as the basis for scenario specific modeling efforts. A high-level functional architecture for offensive mining operations to include deployment, loiter, engagement, recovery and relocation of offensive mines was developed and is discussed in Chapter II. This high-level functional architecture supports the following operational modes: Intelligence, Surveillance and Reconnaissance (ISR), Information Operations (IO), Offensive Attack Operations (OAO), Deterrence by Denial, and Battlespace Management (BM). The Deterrence by Denial operational mode focuses on denying an enemy access to strategic vital locations or assets, protecting undersea cables (key vulnerably for the U.S. economy), and the prevention of movement of threats "through strategic choke points" (Winnefeld and Ahmad 2018, para. 33). Two operational scenarios were developed that focus on the Deterrence by Denial operational mode and are further discussed in Chapter III.

B. PROBLEM STATEMENT

This report presents a high-level operational analysis, simulation, and projection of offensive mine warfare capabilities for the USN. Although the USN has leading edge technology in mine countermeasures, its investment and advancement towards offensive mining has not been as developed in recent years. As Admiral James Winnefeld wrote in July 2018, "The Navy's response has been to dedicate additional resources and intellectual firepower to countermine warfare in an effort to preserve its freedom of maneuver. However, the service has overlooked the other half of the lesson: mines are a cheap and disruptive weapon in naval warfare" (Winnefeld and Ahmad 2018, para. 5). Reviewing and investigating the priorities of the Navy along with the potential capabilities of such weapons, requires a rejuvenation into the idea of offensive mine warfare for the future of the warfighter.

The USN's dominant mentality towards mine warfare in the 21st century is that it is primarily a defensive effort. It is widely understood that the USN's primary concern is with mine detection and countermeasures, with less emphasis on the offensive use of mines in asymmetrical naval warfare (Winnefeld and Ahmad 2018). However, the development of potential force multipliers in asymmetric warfare has become so widespread that it is imperative to construct an idea of how mine warfare may contribute from an offensive perspective. There is an operational deficiency regarding offensive mine capabilities that, if corrected, has the potential to act as a new force multiplier in the modern maritime environment, provided that modern considerations (secure communications, machine intelligence, command and control, signature reduction, modularity, deployability, and lethality) are intentionally included as part of the system design. This research project intends to expand on the ideas presented by ADM Winnefeld to inform operational concept development for offensive mine warfare.

C. PROJECT OBJECTIVES

The USN needs to determine a sufficient method by which to deploy, loiter, engage, relocate and recover mines in the open ocean to assist in the sustainment of our dominance within the undersea domain. This project researches emerging technologies that can be

applied to the deployment, loiter, engagement, and recovery efforts associated with offensive mine warfare and broadens the knowledge base associated with the utilization of mines as an offensive tool. Additionally, this project presents an in-depth analysis of the utility of individual systems within the operational concept. Accordingly, this project develops an initial operational concept and provides a set of requirements for offensive mine warfare to include the functional and component level considerations. Additionally, this project presents a comprehensive architecture defined for the operational activities and systems associated with offensive mine warfare. A modeling and decision analysis process is also included within this report to analyze the benefits and deficiencies of each option available for offensive mine warfare. Lastly, this report provides the development and analysis of the operational simulation to identify the key performance drivers that inform more specific requirements for offensive mine warfare and inform comparison of candidate operational frameworks.

D. SYSTEMS ENGINEERING PROCESS

After studying the various possible systems engineering processes, the group has decided to use a modified version of the "Vee" model informed by the analysis approach presented in (Van Bossuyt et al. 2019). The Vee model is a widely used model that has elements that are well suited to the goals of this project. The Vee model as presented by (Buede 2009) contains steps for not only the design and development of the system, but also the late stages of verification and validation of the completed system. Due to the constraints of this project, a modification was made to the Vee model in order to focus on three major aspects of this project's development: system definition, system modeling, and system analysis.

The system definition process as shown in the resulting Vee model in Figure 1 is composed of both the operational concept and performance requirements. Both the operational concept and performance requirement draw heavily from the results garnered from the stakeholder analysis. Scenarios developed that encompass both architecture/specifications and detailed design represent the system modeling portion of our Vee model. Lastly, the system analysis and last step of this project's development

encompasses the implementation, test and evaluation, and verification stages using a MatLab simulation. As seen by the overlapping steps within each of the three major steps of this project's process, the model allows for work on different stages concurrently. Due to the small project group size and the flexible nature of the project, this concurrent project development allows this project to develop a theoretical operational concept while also testing it using modeling and simulation methods.

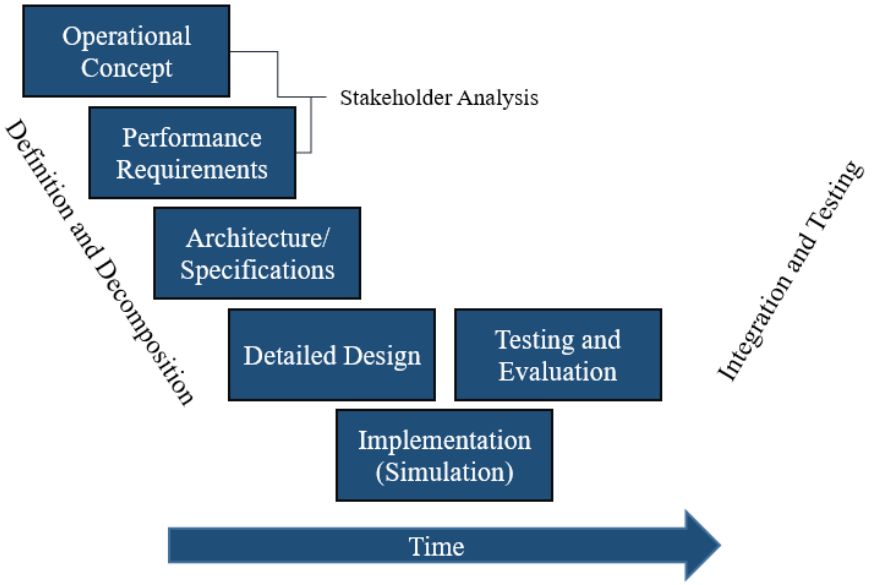


Figure 1. Modified Vee Model for OMW. Adapted from Buede (2009).

II. PROJECT BACKGROUND

A. STAKEHOLDER ANALYSIS

The first step in the systems engineering process, identified in Chapter I, is stakeholder analysis. A full stakeholder analysis table is available as Appendix A. By starting with stakeholder analysis, the project was better able to hone its focus on the actual needs of the USN in regards to offensive mining from stakeholders who have expertise or translational expertise on the subject matter. The major stakeholders that were identified during stakeholder analysis are NSWC Panama City, PEO USC, PMS340 and the submarine community to include Commander Submarine Force (CSF), N97 (Undersea Warfare) and PEO Subs. A number of naval research organizations, program offices and operational commanders comprise the list of stakeholders. This maximized the amount of input received and produced a thorough list of requirements and capabilities. The major concerns that were pulled out of the table presented in Appendix A are the deployment, engagement, loiter, relocation, and recovery of offensive mines. Accordingly, each of those concerns are represented in the operational concept presented in Figure 2 and are used as the bases for the definition of appropriate evaluation measures.

B. NEAR-FUTURE MINE DEPLOYMENT CAPABILITIES

Prior to development of a systems architecture for offensive mining, it is worthwhile to review the existing platforms that may be used in support of offensive mine warfare. The operational concept discussed in this report relies heavily on the use of unmanned vehicles, both undersea and airborne, to accomplish the functions of delivering mines to their required locations and possibly supporting other functions of the offensive mine warfare operation. While there are many platforms in the UAV and UUV markets today, very few possess the payload capacity and on-station time required to adequately perform the full range of offensive mine warfare operations.

One undersea platform, the XLUUV (Extra Large Unmanned Undersea Vehicle), could be a viable candidate for an undersea mine deployment asset. Currently, based on Boeing's Echo Voyager prototype, the Orca XLUUV has been recently awarded a contract

for production with one of its primary missions being mine countermeasures (MCM) (Baker 2019). The Orca XLUUV has several attributes that would also make it suitable as a mine deployment and recovery asset. At 56.6 cubic meters and 7.3 metric tons, its payload capacity exceeds that of other widely used UUVs, and its ability to operate semi-autonomously for extended periods of time make it uniquely suited to carry out the functions described in this report (Baker 2019). Other agencies, including the United Kingdom's Ministry of Defence, are also conducting research into XLUUV technology, which may result in a platform more suitable for offensive mine warfare operations (Baker 2019).

UAV platforms for delivery of offensive mines are also undergoing testing and could prove to be a viable alternative to UUVs. Similar to the UUV requirements described previously, the UAV platform used for offensive mine operations would require a sufficiently large payload capacity, on-station time, and range in order to be effective. The most likely candidates would be carrier-based platforms that have the size, speed, and range to effectively deliver mines and provide support. Unlike the Orca XLUUV, currently no carrier-based unmanned aircraft have MCM as a primary mission (Baker 2019). However, there are carrier-based platforms currently in development that provide promising alternatives or baseline technology to develop an offensive mine warfare UAV platform. One such platform, the MQ-25 Stingray, is currently undergoing testing to serve as a refueling platform for other carrier-based aircraft. Due to its size, range, and payload capacity, it may also be a viable candidate for a mine delivery asset (Naval Air Systems Command n.d.).

C. CURRENT MINE CAPABILITIES

A review of current mine capabilities has shown that the United States currently employs two types of mines: the Quickstrike mines and the Submarine Launched Mobile Mine (SLMM) (MK 67). The Quickstrike mines, which provide a quick-response mining capability, include the MK 62 (500 lbs.), MK 63 (1000 lbs.) and MK 65 (2300 lbs.). These mines are airdropped into shallow bodies of water (less than 300 feet), and target submarines, and surface ships. The Quickstrike mines are bottom mines based on general-

purpose bombs that are deployed by aircraft (Committee for Mine Warfare Assessment 2001). The delivery platforms for the Quickstrike mines include the P-8A, F/A-18, P-3C Orion, and Air Force B-52H to deliver all Quickstrike series mines; the B-1B to deliver Quickstrike MK 62 and MK 65 mines; and the B-2 to deliver Quickstrike MK 62 mines (Committee for Mine Warfare Assessment 2001). The MK 62 and MK 63 are conventional bombs, which allows aircraft carrier air wings to conduct mine operations without carrying dedicated mines as additional ordinance (Lynch and Truver 2018). The bomb tail of the Quickstrike mine includes battery and a variable-influence target detection device (TDD) MK57. The TDD MK57 detects targets with both magnetic and seismic stimuli. It has two types of response configurations, magnetic only or a combination of magnetic and seismic (Lynch and Truver 2018). The Navy is currently upgrading the Quickstrike mines with the MK 71 TDD. This firing mechanism can sense magnetic, seismic and pressure signatures and can be programmed with more advanced target processing and counter-countermeasures algorithms. This will improve performance against different target classes and the response to future threat targets. The Navy has fielded the MK 71 TDD for the Quickstrike MK 65 and as of 2018 was undergoing final qualification testing for using the Quickstrike MK 62/63 mine systems (Lynch and Truver 2018). Two near-term upgrade programs for the Quickstrike family include the Quickstrike-J and the Quickstrike-ER (Trevithick 2018). The Quickstrike-J "combines the mine with a GPS guided Joint Direct Attack Munition (JDAM) guidance package" and the Quickstrike-ER "adds a pop-out wing kit" (Trevithick 2018, para. 5). Both upgrades reduce risk to the aircraft and increase the speed at which a minefield can be laid by allowing them to employ mines from greater altitudes (Trevithick 2018).

The Submarine Launched Mobile Mine (MK 67) is a 2,000-pound bottom mine that combines a modified MK 37 torpedo with a mine warhead (Committee for Mine Warfare Assessment 2001). The SLMM is useful for attacking surface ships and submarines in shallow water (up to 600 feet). Launched from fast attack submarine torpedo tube, the SLMM covertly transits to a predetermined location and waits for enemy vessels. It is particularly useful for mining areas that are not accessible to other mines (Lynch and Truver 2018). There are challenges associated with changing the load-out of a submarine

to support minefield deployment. On Los Angeles class submarines, loading and unloading weapons is an all-day evolution. The weapons shipping hatch is converted with additional rigging gear installed and the forward passageway is reconfigured. The weapons are loaded onboard and stowed in the torpedo room one weapon at a time. It is a very slow and manual operation with hydraulics doing the heavy lifting. Additionally, the mining mission is a low priority for both the mine delivery assets and their mine load-out capacity. Mining is a secondary or tertiary mission for these submarines and operational control of the assets falls outside of the mine warfare commander (Dulla 2019). A near-term upgrade option for this type of mine includes repurposing excess MK 67 SLMM warheads to make Clandestine Delivered Mines (CDM). These mines are designed to be delivered by submarines and Large Displacement Unmanned Vehicles (LDUUV) (Lynch and Truver 2018). Recent Navy budgets have funded projects to develop UUVs with the capability to deliver CDMs (Trevithick 2018).

D. OPERATIONAL CONCEPT

Based on the review of existing technologies and systems, an Operational Concept is developed to serve as the starting point for the systems architecture. A visual means to better communicate and understand the Operational Concept is through the development of an Operational Concept Diagram in the form of an OV-1. The OV-1 diagram in Figure 2 shows the various “players” that interact with the deployment of the offensive mining systems in a non-specified battle space.

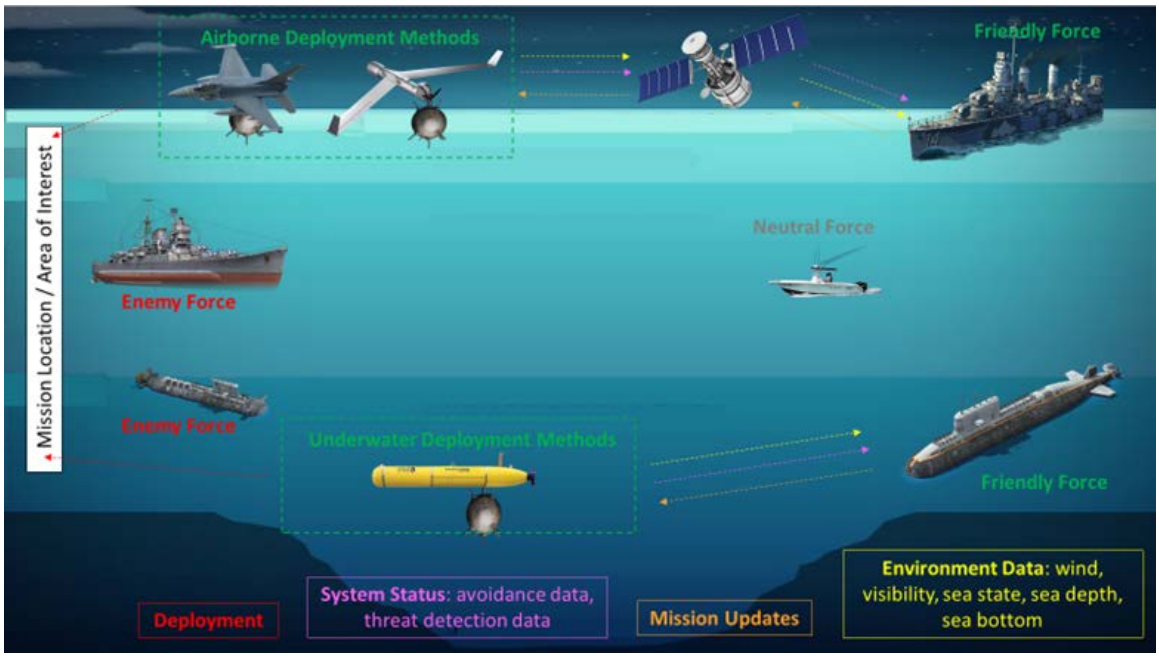


Figure 2. OV-1 for Offensive Mine Warfare

There are several important relationships and definitions in Figure 2 that require additional information. Note that UUVs and UAVs are controlled remotely by a friendly force commander to deploy and recover offensive mines. The system must be able to operate in such a way that friendly forces in the same area of interest are able to communicate with the mines, the delivery units, as well as the command and control (C2) assets in control of the UUVs/UAVs. The accommodation of asymmetric, multi-faceted force compositions is critical for the implementation into modern Navy tactics and doctrine, especially in littoral waters where mine warfare would most likely play a pivotal role. Additionally, Figure 2 emphasizes the factors related to the successful deployment of offensive mines highlighted in the boxes on the bottom of the diagram (Deployment, System Status, Mission Updates, and Environment Data).

E. CONTEXT MODEL

The context diagram for the system of systems within OMW is presented in Figure 3 that highlights the elements necessary to perform an OMW mission. It presents the complex interactions between the OMW systems and the external elements that contribute to the overall performance of the OMW operations. The major external elements

identified include neutral / friendly forces, external threats, environment, and communications systems. Note that there are two major subsystems within the context of Offensive Mine Warfare: Offensive Mine Operations and Offensive Mine Planning.

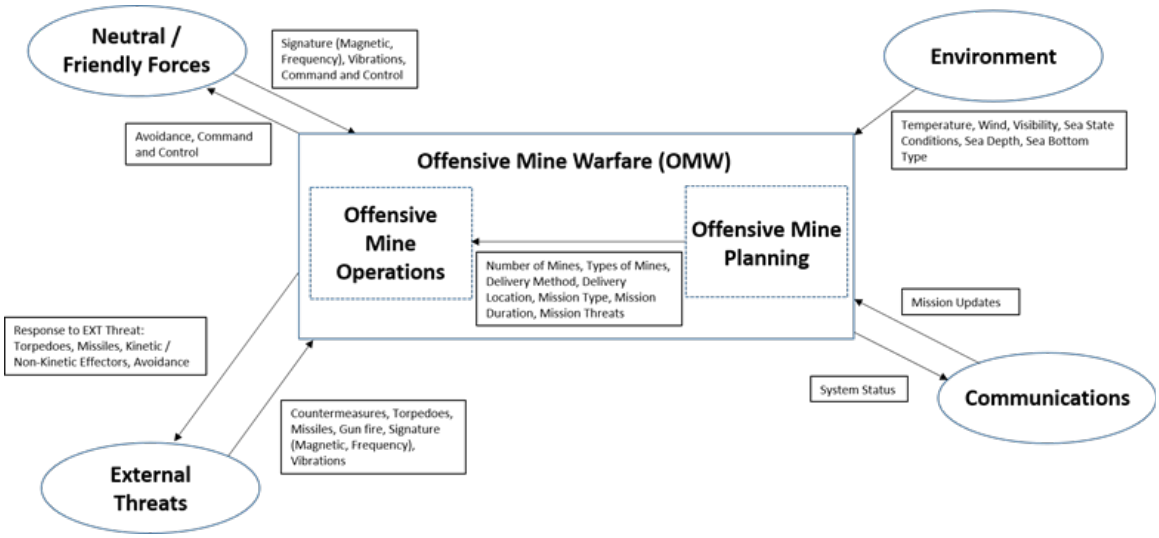


Figure 3. OMW Context Model. Adapted from Frank et al. (2014).

Offensive mine planning defines the number of mines, types of mines, delivery method, delivery location, mission type, mission duration, and mission threats to offensive mine operations based on receipt of external threat data. Friendly and neutral forces input a signature or vibrations to OMW which triggers an avoidance response from the OMW system. Additionally, OMW and friendly forces exchange command and control data. External threats input a signature that initialize the use of weapons (such as torpedoes, missiles, gun fire) to attack and deter OMW systems. These external systems provide the mission operators with the necessary information needed to direct minefield layout and deployment location. OMW outputs a response to the external threat to include avoidance or use of an effector to engage the threat. The communication systems, which exchange threat data (location, course, bearing, and speed) input mission updates to OMW and the output is directly translated into system status updates. Finally, the environment inputs factors that influence OMW operations include temperature, wind, visibility, sea state conditions, sea depth and sea bottom type. The exchange of external threat, friendly, and

neutral force data translates directly into the variability of minefield deployment and relocation in real-time as data is exchanged. Understanding the exchange of data between the OMW and external systems helps isolate the primary functions of the OMW, which are to deploy, loiter, engage, and recover/relocate mines as they are directly tied to these data exchanges.

The objective of this system context model is to define the external factors that need to be considered in developing a complete set of system requirements and constraints. Notably, the OMW system must support multiple physical environments, threat environments, and communication environments.

F. INITIAL FUNCTIONAL HIERARCHY

The functional hierarchy for offensive mine warfare operations, seen in Figure 4, is structured through four operational functions: deploy, loiter, engagement and recovery/relocation. With proper employment, these functions are the fundamental aspects that will result in a successful application of the system. A more detailed explanation of the requirements listed in the hierarchy can be found in Appendix B.

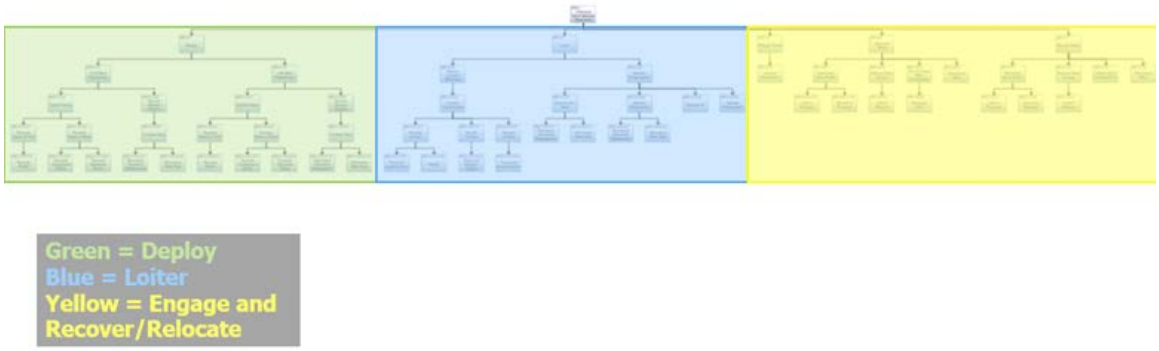


Figure 4. OMW Major Functions

1. Deploy

Deployment of the system is the first system function, allowing for the option of a UUV or the UAV. Each method mitigates safety risks to the operator. The unmanned

system allows the crew to operate and communicate with them from a distance instead of having to be directly in the battle space.

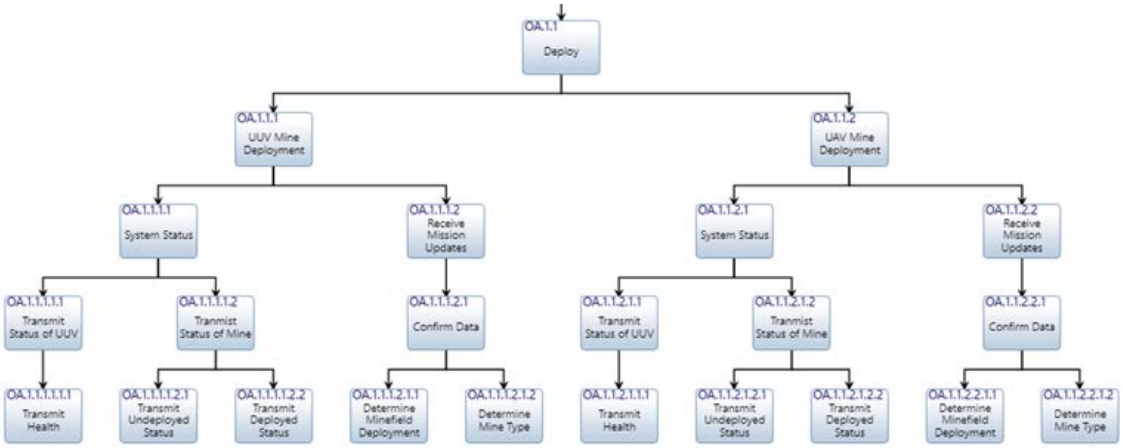


Figure 5. Decomposition of Deploy

Figure 5 shows how both the UAV and UUV deployment methods are broken down into lower level functions: system status and the receipt of mission update. System status has two major transmission activities: the health of the vehicle and the deployment status of the mine.

The health of the vehicle with regards to the motor, fins and battery life provide valuable feedback on the vehicle's status back to the operation crew. This information is important for understanding the electrical and mechanical systems, when it is safe for the vehicle to continue a mission, or to return to base for maintenance or repair. The status of the mine deployment allows the operator to receive feedback in real-time to determine if the mine was successfully released from the vehicle and whether or not to continue the mission. Real-time communication between ships and the unmanned systems allow the operator to confirm data was received from ships force to the system. The operator can also change mission details to reflect the current mission needs and determination of what minefield deployment and mine type should be implemented.

2. Loiter

Loiter is the second function of the system developed for OMW. As shown in Figure 6, loiter enables the vehicle to plan a course of action to monitor the environment and assign threat levels to targets (neutral, friendly or hostile) within the battlespace. Once the targets are classified, the vehicle would then decide on the course of action (COA). Friendly contacts would be tracked, charting a course to avoid and notify the contact of its presence in the environment. Neutral contacts would be treated similarly without notification to the contact. Hostile contacts would be tracked and monitored to ensure that the vehicle cannot be detected by the threat as well as confirm range, bearing, speed, and course to place mines for necessary defensive action. The vehicle is constantly monitoring the sea sate and bathymetry of the environment, preparing for the correct type of deployment of mine field and type required for the mission. Sound velocity and temperature must also be sampled and used to provide the vehicle with an understanding of the acoustics in the surrounding area.

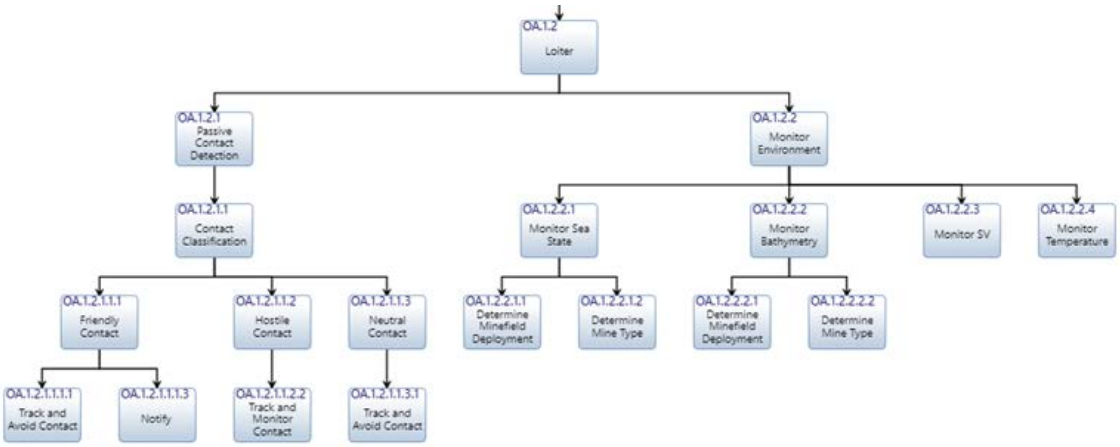


Figure 6. Decomposition of Loiter

3. Engagement

The engagement function, as seen in Figure 7, follows the loiter phase and the vehicle executes the COA that was determined during this phase. Depending on the target type, the vehicle will need to execute the mine deployment necessary for defensive action against hostile targets and mine field deployments based on the loiter assessment and mission.

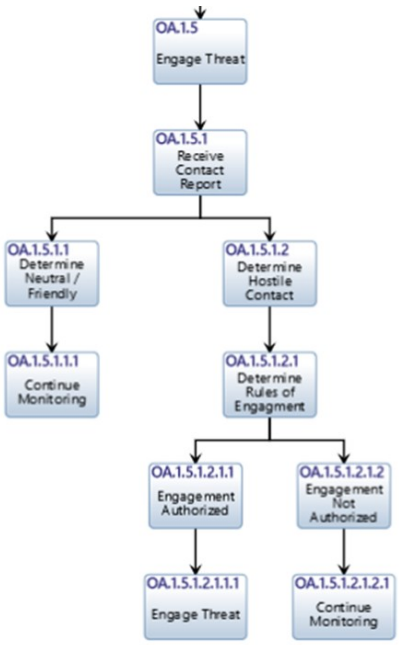


Figure 7. Decomposition of Engagement

4. Relocate and Recovery

The final major function is the relocation and recovery of the weapons and sensors. As seen in Figure 8, this can be decomposed into determining the health of the weapon, retrieving the weapons and sensors location and finally delivering the systems to another location or in the safety of another friendly force. Executing all of these actions successfully requires the vehicle to receive the current location of the weapon or sensor. The vehicle then must decide if the current state of the weapon/sensor is secure to be recovered without damaging the weapon/sensor or the vehicle. If the weapon/sensor is safe to transport, an extraction of weapon/sensor will be executed by either retrieval and recovery or concurrently retrieval and redeployment to a new area of interest.

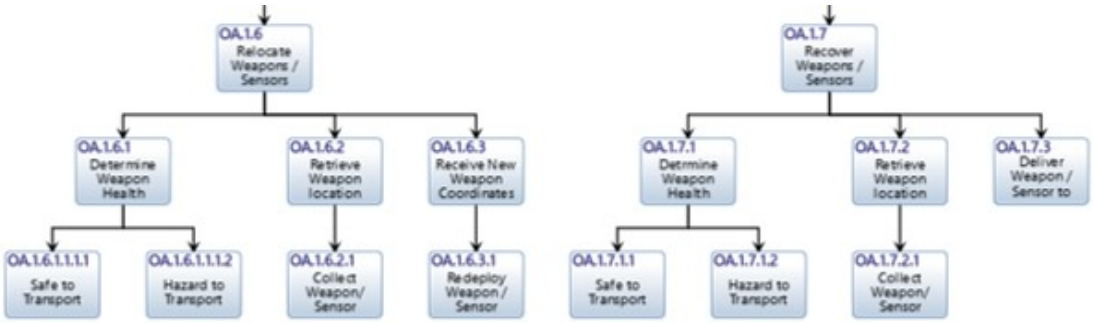


Figure 8. Decomposition of Relocate and Recover

G. EVALUATION MEASURES

In order to determine the measures of effectiveness (MOEs) for the operational mine warfare concept, the first step was to determine what defines a successful offensive mine operation. The functional hierarchies described previously in this report have a number of different metrics by which they can be measured, but only specific measurable metrics will help determine the effectiveness of the offensive mining operation. The four top-level functions of the operational concept—deployment, loiter, engagement, and recovery—each have a separate criterion for which they must be successful if the system is to be effective. The MOEs and MOPs described here are presented in Table 1.

Table 1. Evaluation Metrics

MOE 1.1: Deliver/Deploy	MOE 1.2: Engage	MOE 1.3: Loiter	MOE 1.4: Relocation/Recovery
Time to deploy active minefield (T_{total})	Number of enemy contacts entering the AOI ($N_{Entered}$)	System on-station time ($T_{On\text{-}Station}$)	Assets lost after mission end (N_{lost})
MOE 1.1 MOPs	MOE 1.2 MOPs	MOE 1.3 MOPs	MOE 1.4 MOPs
Transit Time to AOI ($T_{transit}$)	Number of unharmed enemy contacts ($N_{unharmed}$)	Reliability of Mines (R_{mine})	Number of mines successfully recovered ($N_{recovered}$)
Deploy Time of Mine (T_{deploy})	Number of damaged enemy contacts (N_{harmed})	Number of Mines (N_{mine})	Number of mines lost (N_{lost})
Number of Mines (N_{mine})	Number of enemy contacts deterred from AOI ($N_{deterred}$)		Number of UUV/UAVs lost (UV_{lost})
Number of UUV/UAVs (N_{UV})	Spacing Between Mines ($Space_{Mine}$)		Reliability of Mines (R_{mine})
Reliability of UUV/UAV (R_{UV})	Blast Radius (r_{Blast})		Spacing Between Mines ($Space_{Mine}$)
Speed of UUV/UAV (Spd)	Number of Mines (N_{mine})		Length of Minefield ($L_{MineField}$)
Spacing Between Mines ($Space_{Mine}$)	Length of Minefield ($L_{MineField}$)		Number of Mines (N_{mine})
Length of Minefield ($L_{MineField}$)			Number of UUV/UAVs (N_{UV})
Maintenance Time of UUV/UAV ($T_{Maintenance}$)			
Carrying Capacity of UUV/UAV (N_{cap})			

The loiter function for the system is effectively defined by how long the system can remain operational. The loiter time is limited by whichever asset necessary for offensive mine operations has the shortest on-station time, whether that be the mines themselves, the sensor platform, or the C2 asset. Any limit on the on-station time of any required asset is a decrease in the effectiveness of the overall system. The MOE for the loiter function, then, is the on-station time for the entire system, and is determined by the on-station capability of the individual assets.

For the deployment function, the most important metric is time spent laying the minefield. Due to the nature of mine warfare, where the minefield must be operational prior to any engagements, minimizing the time spent preparing the battlespace—in this case, placing the mines in the appropriate location—is of the utmost importance. Sufficient time before any engagements take place must exist for the minefield to be effective as an offensive weapon. The time to deploy the minefield is therefore the MOE for deployment, and must be minimized.

The engagement function exists to deter enemy forces from entering a certain area, specifically the Area of Interest (AOI) in which the friendly or neutral forces exist over a length of time. The denial of access to a specific area is a cornerstone capability of the mine warfare concept, and is dependent on an effective engagement function. The effectiveness of the engagement function is therefore measured by the number of enemy contacts that are able to enter the AOI, and is a representation of how well the mines and supporting assets work as an integrated system.

For the relocation and recovery function, the most important metric is the number of mines and delivery assets that are successfully recovered post-engagement. Except for any mines lost to engagements, an effective system would be able to recover as many unused mines and delivery assets as possible. Therefore, the MOE for the relocation and recovery function is the number of assets recovered. This MOE is not constrained by time other than normal operational considerations outside the boundaries of this concept of operations.

Each of the previously described MOEs are decomposed into a number of measures of performance (MOPs). These MOPs are factors that play a role in determining the MOEs of each function, and will be used later on in the simulation developed for this concept of operations. For real-world operations, the MOEs do not necessarily correspond to inputs and outputs of the system, since some of them cannot be changed or are dependent on the environment. However, for the purposes of the simulation, the MOPs form the basis of the inputs and simulation characteristics. The discussion of MOEs and MOPs is expanded in the modeling and simulation discussion in Chapter IV.

III. SYSTEMS ARCHITECTURE

A. OPERATIONAL VIEW

In this chapter, operational views of offensive mine warfare in two different battlespaces are presented. Scenario 1 is an operational view of offensive mining in a strait and Scenario 2 is an operational view of offensive mining in the open ocean.

1. Scenario 1

As seen in Figure 9, Scenario 1 is a straits transit mission in which a surface asset, in this case a guided missile destroyer (DDG), is tasked with escorting high-profile civilian shipping vessels through a contested strait where there has been some initial warfare actions between nations (Figure 9). Prior to the transit, a separate command responsible for providing the mines and deployment assets (UUVs or UAVs) is informed of the mission requirements, and the regional warfare commander is faced with the first of several possible courses of action (COAs). Either of the following options for C2 is viable:

- The fast-attack submarine (SSN) deployed to the region is notified of the transit and ordered to act as C2 asset.
- The surface vessel (DDG) is tasked as C2 asset.

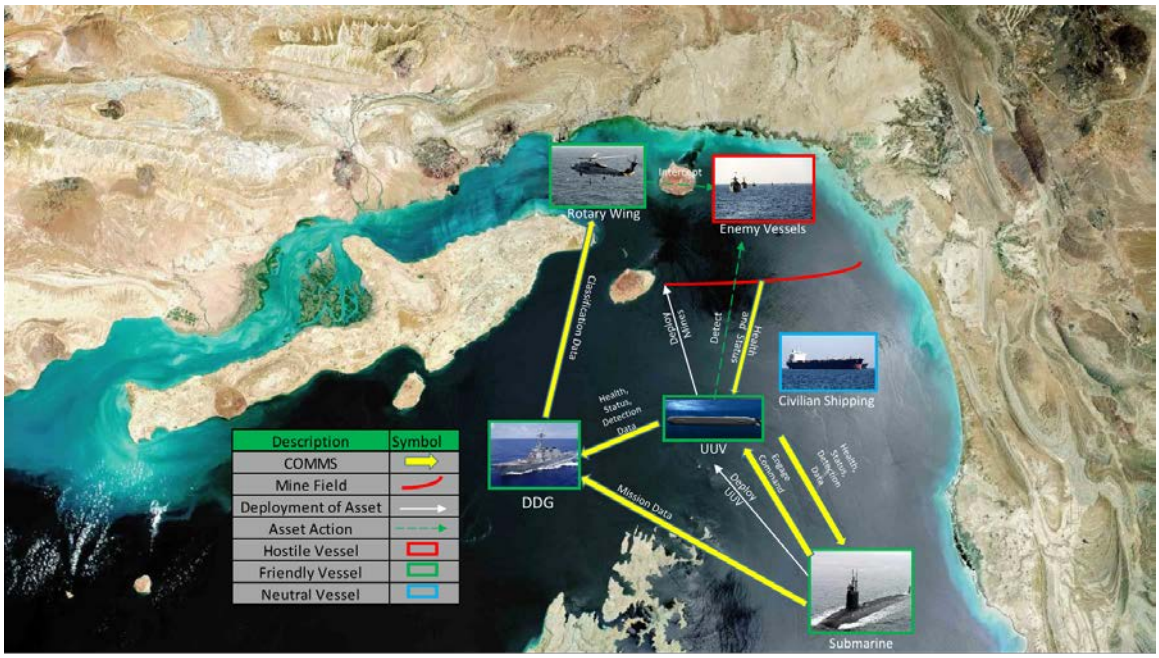


Figure 9. Scenario 1 OV-1

For the purposes of this scenario, an assumption is made that due to Office of Naval Intelligence (ONI) recommendations based on current regional intelligence, the SSN is selected as the C2 asset, and the use of UUVs for mine delivery is chosen. Country Orange—who has a strong naval presence in the region—is planning to demonstrate their influence in the region by intercepting the escort convoy using an unknown number and type of intercept vessels. Only the most likely intercept course is known, and therefore an offensive mining operation has been ordered to counteract this effort.

Prior to the transit, the warfare commander communicates with the external UUV command as well as the C2 asset and provides the number, type, and deployment pattern of the upcoming mine deployment. The number and pattern of mine deployment is based on several factors, including geography, mine capabilities, battlespace requirements, and maneuver schema. According to the plan of action, the SSN will retain operational control of the UUVs and mines, but may delegate relocation and engagement responsibility to the DDG as required (this control scheme would be reversed if the DDG were selected as C2 asset). After receiving the mine deployment plan, the external UUV command prepares the UUV (or multiple UUVs, if required), loads the mines, and deploys the UUVs to the area

of interest (AOI). Once on-station, the UUVs deliver the mines per the briefed deployment plan. Control of both the UUVs and the mines is transferred to the C2 asset. There are two alternative courses of action:

- The mines use self-contained sensors and communication equipment to send real-time health, status, and detection information to allied assets in the region, and the UUVs return to base after deployment.
- The UUVs remain on-station and report the mine health, status, and detection information to the SSN using on-board communication equipment. In this case, the UUVs would also perform passive sonar detection to locate and classify contacts ensuring friendly forces know the location of mines and so the system can avoid contact by hostile forces.

The DDG begins to escort the civilian vessels in accordance with the escort brief. During the transit, either the UUVs or mines (depending on the alternative course of action) in the formation detects a group of several Country Orange vessels intercepting the convoy at high speed. The chosen asset (UUVs or mines) detects the vessels, classifies them using prior intelligence and classification capability, and relays this information to friendly assets in the area.

At this point, the next steps taken are determined by the current rules of engagement. If engagement is authorized, the C2 asset (in this case, the SSN)—or, if tasking has been delegated by the C2 asset, the supporting asset (DDG)—delivers the engagement command to the mines, via the UUVs. Upon receiving the command, the mines carry out the engagement order. In this case, one or more of the intercepting vessels is destroyed.

If the rules of engagement do not allow for direct engagement, the asset chosen by the two alternatives delivers location and identification data to the DDG, which then orders its anti-surface warfare (ASuW) rotary wing element to deter the intercept vessels using predetermined intercept procedures. Using the data gathered by the mines or the UUV, the rotary wing element is given precise location, direction, speed, and classification data prior to intercept.

After the escort mission, the decision to either leave the mines in their current location for use by other friendly assets or have the UUVs recover the mines using their transmitted location data must be made. Eventually, the mines must be recovered, but the system should function in such a way where operational control can be transferred between assets to facilitate continued use of the mines. The scenario ends when the C2 asset and warfare commander either recover the mines or transfer operational control to another asset.

The functional allocation for Scenario 1 is presented in Table 2. The functional allocation is a morphological chart that maps a physical hierarchy to the top-level functions. The first row of the chart are the top-level functions of the operational concept—deliver/deploy, loiter, engage, and recover, and each are matched to potential physical systems that would be able to perform the function. The operational effectiveness of each of the physical systems proposed for Scenario 1 will be analyzed in the simulation developed for this concept of operations.

Table 2. Functional Allocation and Alternatives for Scenario 1

Function Allocation				
Deliver	Deploy	Loiter/Communicate	Engage	Recover
Submarine	Submarine	XLUUV	SLMM (MK-67)	Submarine
XLUUV	XLUUV	UAV	Quickstrike (MK-2,63,65)	XLUUV
UAV	UAV	SLMM (MK-67)	Clandestine Mine	
P-8	P-8	Quickstrike (MK-62,63,65)		
		Clandestine Mine		

2. Scenario 2

As seen in Figure 10, Scenario 2 is a navigation mission involving a carrier strike group (CSG) proceeding along their intended movement to an area of operations (Figure 10). Unlike Scenario 1, the architecture is fixed, and is based on a carrier strike group (CSG) force structure composed of an aircraft carrier (CVN), three DDGs, and a guided missile cruiser (CG). During this open-ocean transit, the strike group is ordered to maneuver through an area of territorial waters claimed by Country Red despite international disagreement with the claim. In order to combat the possible confrontation with Country Red forces in the region, the CSG Commander orders offensive mines be placed in a predetermined pattern emphasizing deterrence since moving a CSG through this constitutes the expectation of enemy aggression. The number and pattern of the mines is determined by geographical constraints, operational constraints, and requirements set

forth by the strike group commander prior to the transit. For this scenario, it is assumed that the pattern is a line of mines placed in between the CSG and the point from which the combatant vessels will most likely approach.

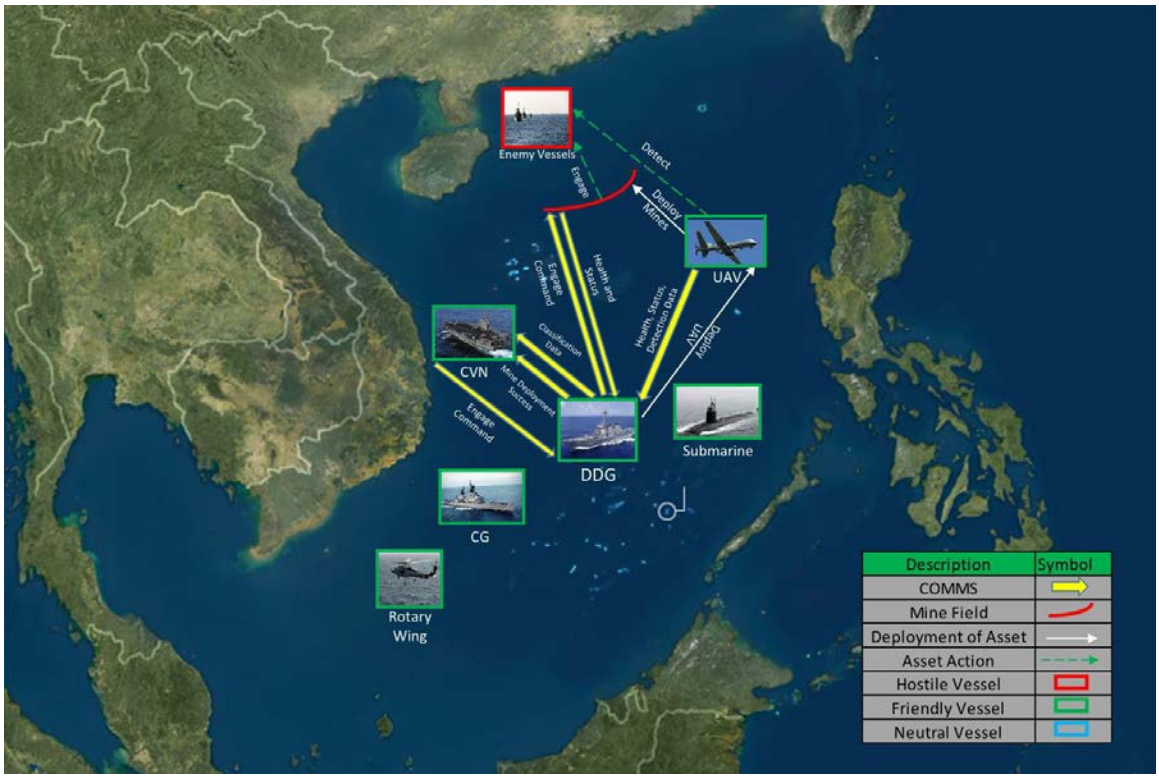


Figure 10. Scenario 2 OV-1

As in Scenario 1, the first choice made by the strike group commander is to decide which asset will act as the C2 asset. Multiple options are available, including:

- One of the DDGs in the strike group will act as C2, with either a UUV or UAV as the delivery asset. In this case, the SSN and CVN/CG would act in a supporting role.
- The SSN will act as C2, with a UUV as the delivery asset. In this case, all surface assets and any available UAVs would act in a supporting role.

- The CVN or CG would act as C2, using a UAV or UUV as the delivery asset. Any ship in the CSG may act in a supporting role.

Based on available intelligence data and operational requirements, the strike group commander designates a DDG in the strike group as the mine deployment C2 asset and they are given operational control over a mine delivery UAV which is launched from the CVN. Using several consecutive mine deployment sorties, the UAV deploys the mines to the predetermined locations. Based on the designed capabilities of the two subsystems, either the mines themselves or the UAV transmits the mine health and location data to the C2 asset. The DDG then reports successful deployment to the CSG Commander.

As the CSG transits, one or more mines detect a large combatant vessel and a subsurface combatant vessel holding station in the vicinity of the strike group. The location and classification information are sent to the C2 DDG, who relays the information to the CSG Commander. The reported distance is within strike distance of combatant cruise missiles, which gives the CSG Commander early warning to implement the required defensive posture and launch the required fixed and rotary wing alert aircraft.

As with Scenario 1, the existing ROE is the determining factor for the next steps taken by the CSG. In the event that engagement is authorized, the CSG Commander gives the engagement order to the C2 DDG, which then relays the order to the mines. The mines, using location and classification data, supplied by the UAV, engage the combatant vessels. If rules of engagement do not allow for direct engagement, the mines continuously relay the location and classification data to the C2 DDG. The C2 DDG uses this data to recommend defensive posture and use of anti-submarine (ASW) and ASuW assets to deter the combatant vessels.

The same recovery or transfer option is available to the strike group commander after the transit is complete. In this example, it is assumed that there is no follow-up mission scheduled for the area, and therefore mine recovery is in order. After the CSG leaves the area, the friendly SSN in the area is tasked with recovering the remaining mines using its UUV while the CSG continues its transit. Once all mines are recovered, the SSN and CSG report clear of combatant forces and standby for further tasking.

The functional allocation for Scenario 2 is presented in Table 3. The functional allocation is a morphological chart that maps a physical hierarchy to the top-level functions. The first row of the chart are the top-level functions of the operational concept—deliver/deploy, loiter, engage, and recover, and each are matched to potential physical systems that would be able to perform the function. The operational effectiveness of each of the physical systems proposed for Scenario 2 will be analyzed in the simulation developed for this concept of operations.

Table 3. Functional Allocation and Alternatives for Scenario 2

Function Allocation				
Deliver	Deploy	Loiter/Communicate	Engage	Recover
Submarine	Submarine	XLUUV	SLMM (MK-67)	Submarine
XLUUV	XLUUV	UAV	Quickstrike (MK-2,63,65)	XLUUV
UAV	UAV	SLMM (MK-67)	Clandestine Mine	
P-8	P-8	Quickstrike (MK-62,63,65)		
		Clandestine Mine		

IV. SIMULATION DESIGN AND DEVELOPMENT

A. SIMULATION PURPOSE AND GOALS

The primary purpose of this simulation's design is to provide quantitative data in support of an actionable, detailed analysis of the operational concept described in this report. While the simulation is not all-inclusive, the intent is to provide a baseline simulation of the system architecture outlined in the scenarios described in Chapter III. The goals of the simulation are as follows:

- Produce a simulation which accurately models the scenarios described in Chapter III.
- Utilize the previously discussed evaluation measures and functional requirements to the maximum extent possible.
- Provide outputs for the maximum number of evaluation measures possible for quantitative analysis of the proposed system.
- Provide a baseline simulation architecture that can be used for follow-on analysis of later offensive mine warfare operational concepts.

By meeting these goals, the simulation will be able to not only provide usable data for analyzing the scenarios and system architecture, it will also be useful for future efforts in the area of offensive mine warfare and the development of operational concepts. The overall design of the simulation is a MATLAB model that includes measures of effectiveness from both scenarios and can be modified for use depending on the scenario being tested.

B. SIMULATION DEVELOPMENT

1. Assumptions

To accommodate both scenarios, and to establish boundaries to the simulation environment, key assumptions have been established. First, it is assumed that the enemy forces will attempt to engage the friendly forces in both scenarios and will enter the

minefields instantaneously at a random point in space and time during the engagement. The second assumption is that there will be only two types of mines deployed into two separate rows in the minefield. All mines placed in row one are evenly spaced with their proximity to one another based on the length of the minefield inputted by the user. The mines placed in row two are placed in the middle of the spaces between the mines in row one. Figure 11 has a representative layout of this description. Another assumption regarding the simulation is that the UUV and UAV deployment systems will not be a target for opposition forces. For the UUV systems, it is assumed that they will be submerged, and they shall be located a sufficient distance from enemy forces as to not be detected. For the UAV systems, it is assumed that they will be launched early enough to deliver the mines while remaining outside the enemy engagement range, since the mine deployment would occur prior to contact with enemy forces. Finally, the sensors used to determine attack criteria—whether located on the mines themselves or as part of a separate asset—possess sufficient target discrimination capabilities to allow neutral and friendly vessels to pass through safely, while successfully targeting enemy vessels entering the minefield. Additional assumptions can be found in Appendix C.

2. Design

The simulation design consists of integrated modules for the required inputs and functions of the simulation, each composed of separate simulation categories. Prior to development, the simulation inputs were divided into three categories: environmental factors, system structure (architecture), and operational characteristics. The time-step simulation characteristics for the simulation were placed in a separate category. The loiter and recovery functions, while a part of the overall operational concept, were omitted from the simulation for several reasons. Firstly, the loiter function would be ineffective to model since its primary MOE—on-station time—is simply a factor of the lifecycle reliability of the mines being used. While the deployment and engagement simulation conducted later in this report do use placeholder values for mine reliability, these values are estimates and are used for analysis purposes only. The estimate values allow the simulation to include reliability as a factor in mine deployment and enemy engagement. However, the use of those estimates for the loiter function would simply generate a distribution of time that

would be neither accurate nor useful for real-world application. The recovery function is an important aspect to be considered when designing this system but, since it is only done after the battle has been fought and an analysis of that data would not have had an impact on the performance of offensive mine warfare, it was not included in this simulation.

In order to facilitate the development of the simulation, the measures of performance (MOPs) discussed earlier were translated into simulation inputs and outputs. The inputs were placed into the separate categories described above and assigned to one of three iterations of simulation development. The first iteration was the baseline build, and consisted of the minimum required inputs for simulation, including the length of the simulation, number of mines, and engagement distances unadjusted by environmental or operational factors. The first iteration also introduced the minefield layout previously described in the assumptions section. A graphical representation of the minefield layout is presented in Figure 11. Once the first iteration was established, the second iteration of inputs were added, to include reliability factors for the separate components in the system, as well as delivery asset speed and some operational factors. Finally, the third iteration added the environmental factors, including sea state, bathymetry, and non-friendly ship characteristics. The simulation categories and iterations are shown in Table 4.

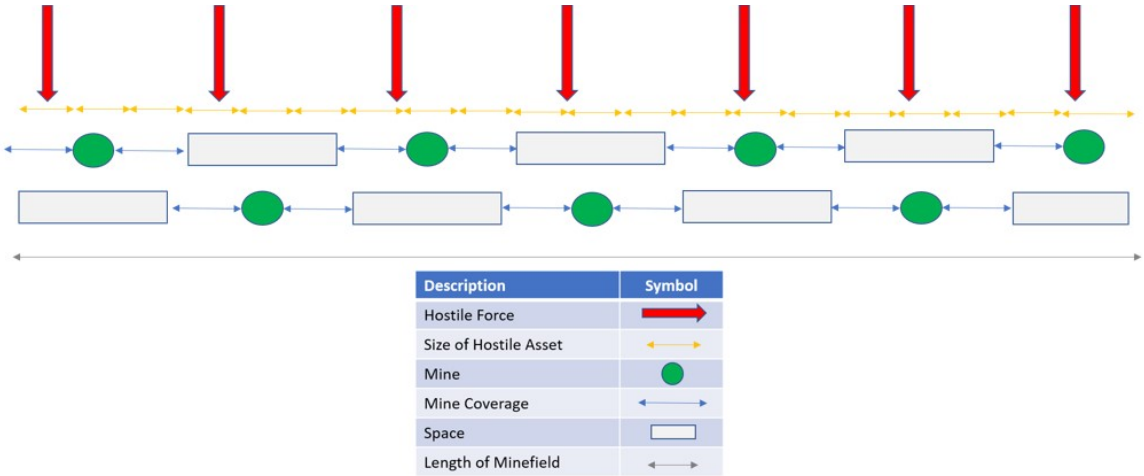


Figure 11. Minefield Layout for Simulation

After the simulation inputs were categorized and the build iterations were planned, the simulation code was created in MATLAB. The first iteration of the code contained the necessary elements to simulate the minefield and associated engagement, without environmental or behavioral inputs. With separate team members working on the different categories and modules, the second and third iterations were generated.

Table 4. Simulation Categories and Iterations

Environmental Inputs	System Characteristics	Operational Characteristics
Sea state	Detection radius	Minefield size
Bathymetry	Mine blast radius	Mine type
Shipping density	Min/Max engagement range	Distance to minefield area
	Mine reliability	
	UUV/UAV reliability	
Simulation Attributes	UUV/UAV mine capacity	
Length of simulation (min)	Probability of detection	
Number of hostile contacts	Probability of kill (P_k) vs. targets	
Number of friendly contacts	UUV/UAV speed	First iteration: Yellow
Number of neutral contacts	Minefield placement time	Second iteration: Orange
Ship size	UUV/UAV maintenance time	Third iteration: Red

The coding architecture consists of separate component modules, one for each category in Table 4 which serve as inputs for the deployment and engagement time-step simulation, as well as the deployment and engagement functions. These functional modules contain the calculations and logic required to run each simulation. The input portion of each module is contained in the "Inputs" MATLAB file, which is kept separate from the calculations and simulation time-step logic. The "Launch" file is used for calculations and simulation logic. After making the necessary calculations and running the simulation, the "Launch" file provides two separate outputs: a calculated time to deploy the minefield and a graphical time representation of the mine engagement function. These outputs provide the basis for the follow-on analysis of each scenario simulation. A graphical representation of the MATLAB simulation is shown in Figure 12, and the full code for the MATLAB simulation can be found in the Supplemental.

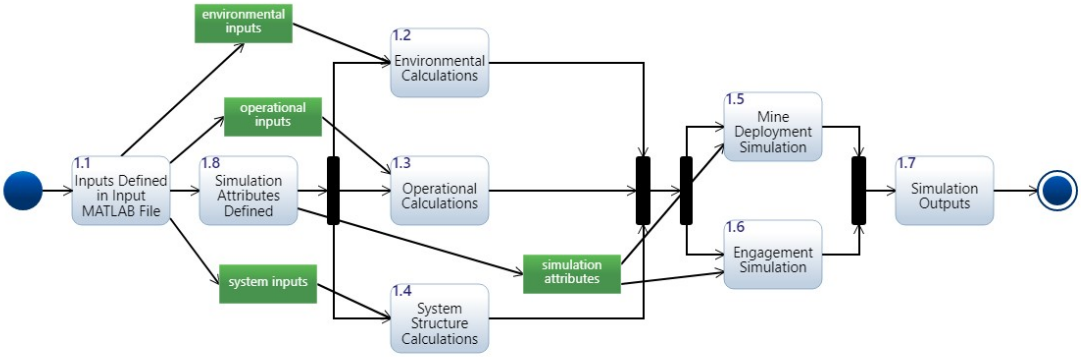


Figure 12. MATLAB Simulation Activity Diagram

V. ANALYSIS

A. SIMULATION SETUP

1. Variables and Constants

The two scenarios described previously were run in the simulation using values derived from their respective environmental and operational characteristics. In order to limit the number of runs required to develop a comprehensive analysis, the model runs focused specifically on variables related to system deployment and engagement. The goal of the scenario was to determine which variables had the greatest impact on the time to deploy the minefield and prevent enemy vessels from entering the AOI, which are the MOEs for deployment and engagement. For Scenario 1, the values used for the simulation represent the straits transit environment, specifically a geographically constrained area with a high level of neutral traffic and a high number of small enemy vessels, as well as the use of a UUV for deployment. The Scenario 2 values reflect the significantly larger area of an open-ocean environment and the use of a carrier-based UAV for deployment. The variables used as inputs for Scenario 1 and 2 can be found in Table 5, and the constants used for the remaining inputs in Table 6. The density of the minefield can be visualized as the minefield size divided by the number of mines, separated into two rows as described in Figure 11. In addition, the mines have been divided into two types in order to simulate having more than one type of mine available for deployment.

Table 5. Simulation Variables

	Number of mines	Number of UUVs/ UAVs	UUV/ UAV mine capacity	UUV/ UAV reliability	Max engagement range (yds) (type 1)	Max engagement range (yds) (type 2)	Mine reliability (type 1)	Mine reliability (type 2)	Minefield size (NM)	Trial
Scenario 1	20	1	4	0.85	250	350	0.75	0.6	1	1
	40	2	10	0.9	300	400	0.85	0.65	3	2
	60	3	16	0.95	350	450	0.95	0.7	5	3
Scenario 2	60	1	4	0.85	250	350	0.75	0.6	5	1
	80	2	6	0.9	300	400	0.85	0.65	10	2
	100	3	8	0.95	350	450	0.95	0.7	15	3

Table 6. Simulation Constants

	UUV/UAV speed (knots)	Distance to minefield (miles)	Mine deployment time (minutes)	Number of hostile contacts
Scenario 1	12	20	5	16
Scenario 2	200	60	5	5

2. Simulation Runs and Results

For each input variable from Table 5, the simulation was run 100 times per value. The use of one variable along with the remaining inputs in each row from Table 5 constituted one trial. For example, Trial 1 used 20 for the number of mines along with the remaining values from the "Trial 1" row in Table 5. Trial 2 also used 20 for the number of mines, but the remaining input variables were those found in the "Trial 2" row. After the third trial, the number of mines was changed to 40, and the process repeated until each value had been tested.

3. Results Analysis

The variables analyzed for each of the output variables of interest are shown in Table 7. Using the output data and resultant box plots, the group was able to determine which variables had the greatest effect on the system in regards to mine deployment time and enemy vessels entering the AOI.

Table 7. Simulation Variables and Relationships to MOEs

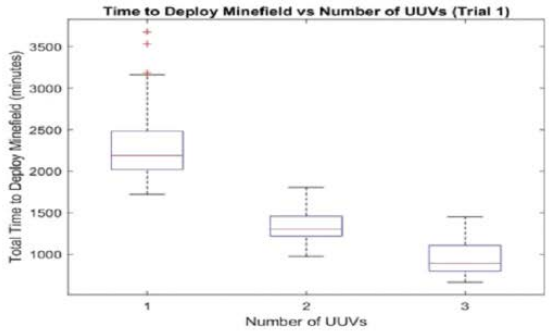
Deployment Time vs.	UUV/UAV Capacity	**Enemy Ships Entering AOI vs.**	Number of Mines
	Number of Mines		Mine Engagement Range
	UUV/UAV Reliability		Mine Reliability
	Number of UUVs/UAVs		Minefield Size

Based on the graphical data provided, the variables were labelled as high, medium, and low effect on the applicable MOE. High effect variables were those whose effect on the system was consistent—that is, it had the same effect on the MOE across all three trials—and changed the outcome of the MOE by more than one standard deviation per change in variable. Medium effect variables were those whose effect on the MOE was consistent, but within one standard deviation per change in value, while low effect variables had neither consistent effect on the MOE nor an effect greater than one standard deviation.

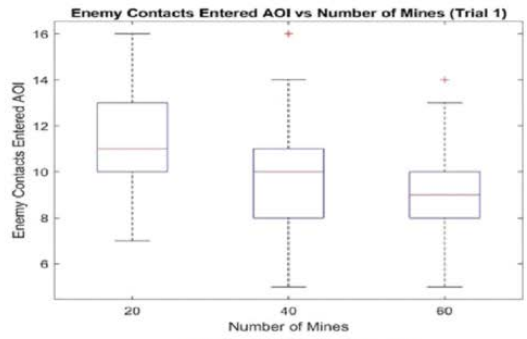
These are displayed in Table 8, with examples of each effect displayed in Figure 13. In Table 8, the variables marked red are high effect, the ones marked with yellow are medium effect, and those marked green are low effect.

Table 8. Input Variable Effect on MOEs

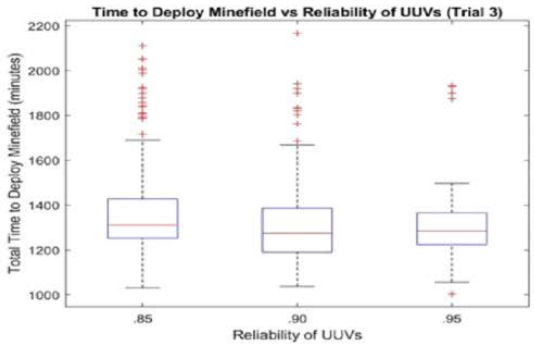
Scenario 1	Deployment Time vs.	UUV Capacity	Enemy Ships Entering AOI vs.	Number of Mines
		Number of Mines		Mine Engagement Range
		UUV Reliability		Mine Reliability
		Number of UUVs		Minefield Size
Scenario 2	Deployment Time vs.	UAV Capacity	Enemy Ships Entering AOI vs.	Number of Mines
		Number of Mines		Mine Engagement Range
		UAV Reliability		Mine Reliability
		Number of UAVs		Minefield Size



High Effect Variable



Medium Effect Variable



Low Effect Variable

Figure 13. High Effect, Medium Effect and Low Effect Variables

In Scenario 1, the variables with the greatest effect on the deployment time (MOE 1) are the capacity of the UUV and number of UUVs available for deployment. The box plots for these high effect variables are shown in Figure 14 and Figure 15. The decrease in the time to deploy as a result of increasing both variables is a result of the decreased transit time to and from the AOI for each UUV. One notable item from the plots is the number of outliers present. These outlier results, marked by a red "+" symbol, occur when all of the deployment assets in the simulation fail and must return for maintenance. This results in a much longer deployment time and, in some cases, a higher number of enemy contacts entering the AOI.

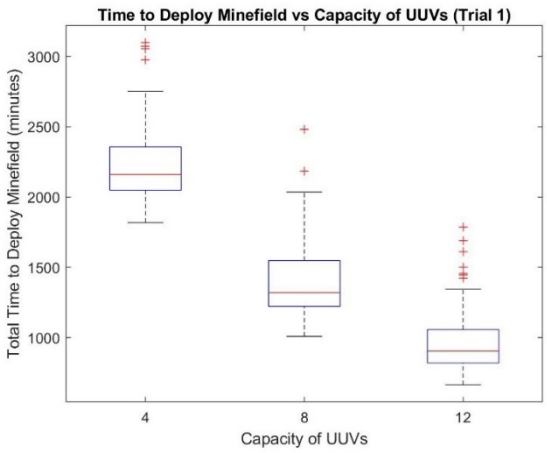


Figure 14. Effect of UUV Capacity on Time to Deploy

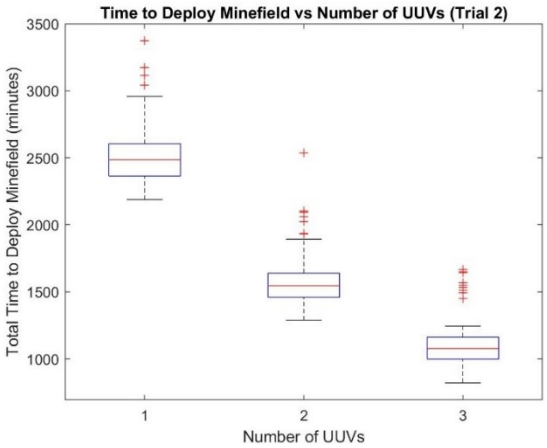


Figure 15. Effect of UUV Number on Time to Deploy

The number of mines and the minefield size had the greatest effect on the number of ships entering the AOI (MOE 2) in Scenario 1. The plots for these variables can be found in Figure 16 and Figure 17. The decrease in the number of ships that entered the AOI as a result of increasing the number of mines was expected. However, increasing the minefield size had the opposite effect by allowing more enemy ships into the AOI. The results showed that the increase in minefield size also increased the area in between the mines themselves, thereby increasing the chance of an enemy ship navigating the minefield without being engaged. Trial 1 (Figure 17), where the number of mines is 20 and therefore too low to accommodate the larger minefield, shows a much more noticeable increase in the number

of ships that enter the AOI. Trial 2 (Figure 18) has a lesser but similar effect as the number of mines is increased to 40. Trial 3 (Figure 19) has the number of mines set to 60, and has almost no effect on the number of ships.

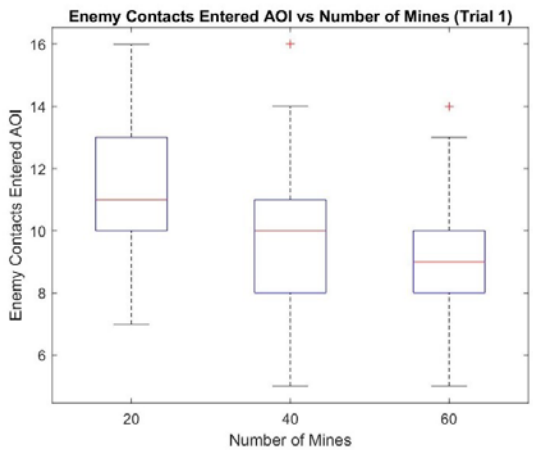


Figure 16. Effect of Mine Number on Ships Entering AOI (Trial 1)

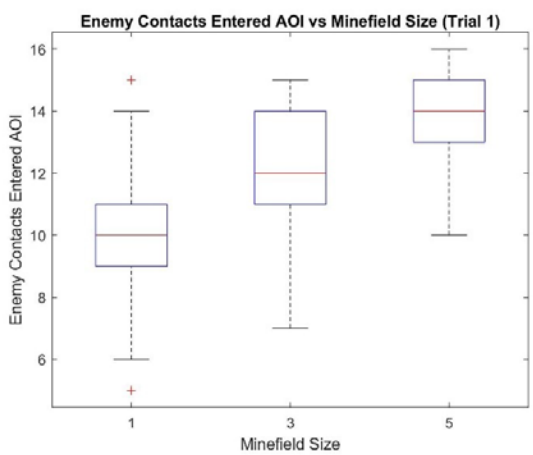


Figure 17. Effect of Minefield Size on Ships Entering AOI (Trial 1)

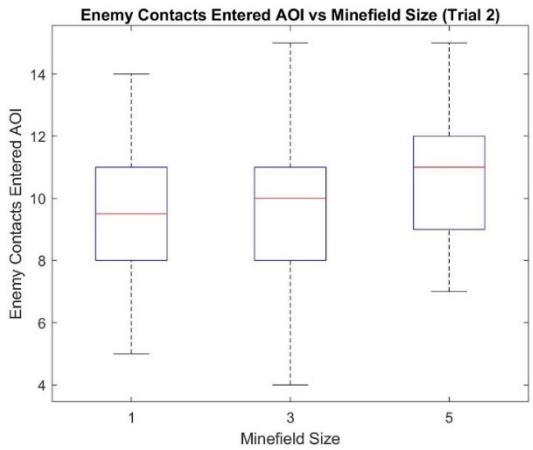


Figure 18. Effect of Minefield Size on Ships Entering AOI (Trial 2)

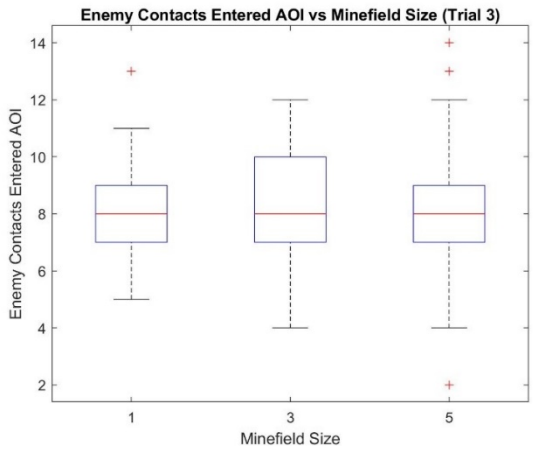


Figure 19. Effect of Minefield Size on Ships Entering AOI (Trial 3)

The simulation results from Scenario 2 are mostly identical results in regards to the effect of the variables on MOE 1. As shown in Figure 20 and Figure 21, the number of UAVs and UAV capacity has the same effect as the UUV variables had in Scenario 1. As in Scenario 1, they are also high effect variables.

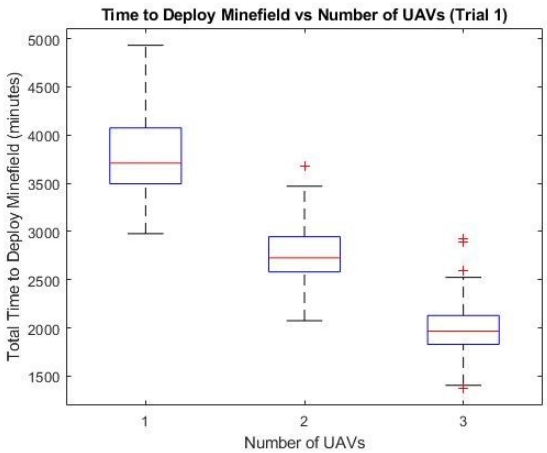


Figure 20. Effect of UUV Number of Time to Deploy (Scenario 2)

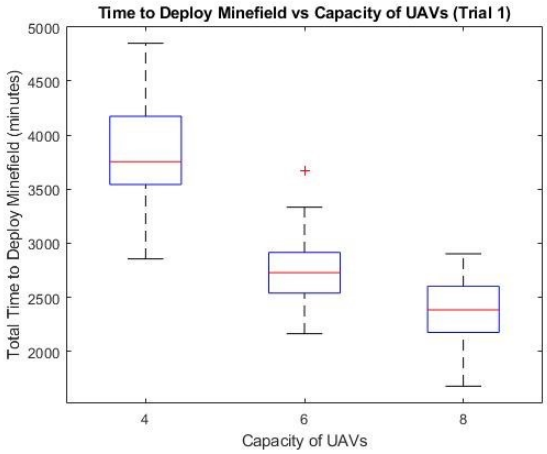


Figure 21. Effect of UUV Capacity on Time to Deploy (Scenario 2)

The effects of the variables on MOE 2 in Scenario 2 were also similar to Scenario 1. However, the increase in number of mines had less of an impact than in Scenario 1, as shown in Figure 22. While the effect was consistent, the low number of ships in the scenario meant that the increase in mines only led to a decrease in at most one ship entering the AOI.

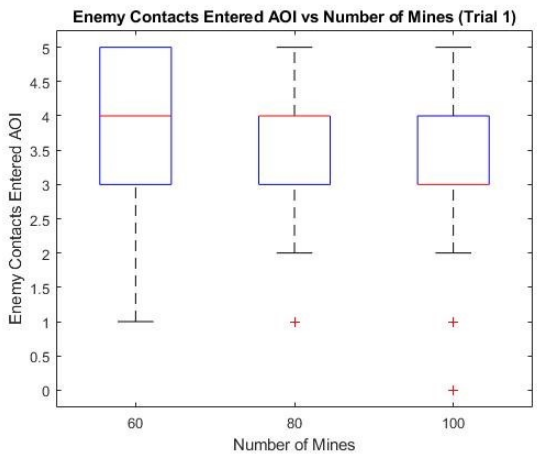


Figure 22. Effect of Mine Number of Ships Entering AOI (Scenario 2)

As with the number of mines, the minefield size impact on the second MOE was reduced in Scenario 2 (Figure 23). In addition, the minefield size effect was inconsistent on the final Trial, as shown in Figure 24. This was indicative of the higher number of mines initially improving the system effectiveness as the size increases from 5 to 10, but then lacking sufficient mines to cover the area of the minefield size of 15. The inconsistency shown in Trial 3 resulted in minefield size being labeled as a low effect variable for Scenario 2, despite the fact that it shares similar characteristics in Trials 1 and 2.

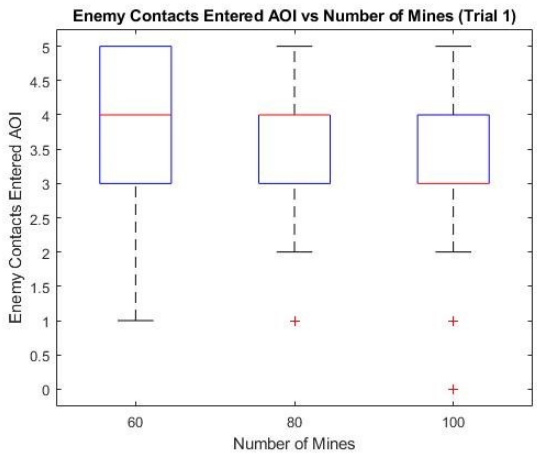


Figure 23. Effect of Minefield Size on Ships Entering AOI (Scenario 2)

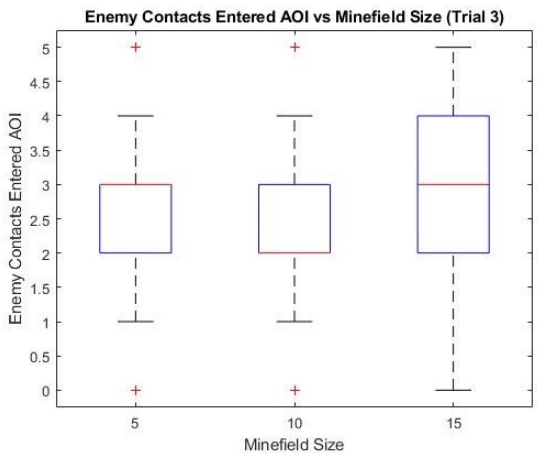


Figure 24. Effect of Minefield Size on Ships Entering AOI (Scenario 2, Trial 3)

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VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

From the analysis of the simulation data, we can make several conclusions concerning the implementation of an offensive mine warfare concept of operations. Firstly, in order for any offensive mine warfare system to be effective, it will require a substantial amount of additional support for the deployed unit requiring offensive mines. As seen in the analysis, multiple large-capacity UUVs or UAVs with enough endurance to remain on-station and employ sensors would be necessary for timely mine deployment and target engagement. The time to deploy is drastically reduced with the use of multiple deployment assets, meaning that maximization of UUV or UAV support assets would be a primary goal. In addition, multiple deployment assets would reduce the probability of all assets failing and provide redundant deployment capability. Unmanned systems that could fill these roles are currently in the development stage, as previously discussed in this report.

It is also apparent from the analysis that any offensive mine warfare system would be a force multiplier and possible engagement early warning system, and should not be considered a replacement for current force protection or engagement procedures. The analysis shows, in both scenarios, a considerable number of enemy ships penetrating the minefield. However, this simulation did not include additional support from friendly naval assets during the engagement. It can be assumed that, if the friendly assets in the AOI were to engage enemy forces along with the offensive mine system, the number of enemy ships penetrating the AOI would decrease. The mine warfare system is not completely effective on its own, but is effective as a force multiplier if deployed prior to an engagement.

Finally, the minefield area should be minimized whenever possible. The minefield is less effective as the minefield coverage area is increased, with consistent results from both scenarios. Because of this, the offensive mine concept should not be considered an effective tool with which to deny an enemy force access to a large area, but as a system to be used in a small, specific location. In summary, in order to be effective, any mine warfare

system would require a significant deployment and support structure, used in conjunction with current naval systems, and be deployed in a confined, limited area.

B. RECOMMENDATIONS FOR FUTURE WORK

Based on the conclusions drawn from this report, two recommendations for future work in regards to offensive mine warfare can be made. Firstly, we recommend that if offensive mine warfare is to be considered a viable system in regards to denial of a large area as opposed to a confined one, research should be conducted into developing a "smarter" type of mine. As discussed earlier, a larger minefield size—and therefore a greater distance between mines—drastically reduces the effectiveness of the system. However, a mine capable of reducing that gap on its own, with some sort of limited propulsion and guidance capabilities, would be able to mitigate that loss of effectiveness and be able to cover the same area as several stationary mines. Also, a "smart" mine capable of conducting its own detection and target discrimination would allow the deployment and support assets to conduct other operations concurrent with the offensive mining mission, allowing for greater flexibility.

In addition, the integration of the mine warfare system, specifically the mines and deployment assets, into current naval systems should be a priority. A flexible offensive mining system presents a threat to friendly forces as well if not adequately communicated to all friendly assets in the AOI. In areas where this type of operation is commonly executed, especially where there is a higher density of neutral and friendly traffic, a dedicated mine warfare command and control system should be implemented to ensure adequate dissemination of minefield location, size, and duration. A smarter minefield, with the ability to communicate with current battlespace awareness and navigation systems, would allow naval forces to safely and effectively operate an offensive minefield using existing equipment.

Finally, further research into the recovery function of the proposed system should be conducted to ensure that any offensive mining system operates with the assurance that any leftover mines can be adequately recovered and removed from the AOI after all conflict is resolved. While not covered in the simulation developed for this report, recovery of the

mines is an equally important functional requirement as deployment and engagement. It should therefore be successfully implemented prior to system use by naval forces.

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APPENDIX A. STAKEHOLDERS

Table 9. Stakeholders. Adapted from Frank et al. (2014).

Stakeholders	Classification (Project, Internal, 1st, 2nd, Boundary)	Type Prioritization (Primary, Secondary)	Level of Involvement in OMW	Interest in OMW Primitive Need
Naval Surface Warfare Center, Panama City (NSWC PC)	Internal	Primary	NSWC PC is responsible for the major testing, developing, and evaluation of major mine warfare systems. Concurrently, they are responsible for the integration of offensive mine technology with disparate naval subsystems.	Has shown interest in the exploration of OMW as an offensive alternative.
NSWC, Future Ship Concept Branch	Internal	Secondary	Focused on the integration and ship designs focused on OMW.	Involved in the requirements design and analysis between underwater and surface ships and their connections with UUV and UAV systems.

Stakeholders	Classification (Project, Internal, 1st, 2nd, Boundary)	Type Prioritization (Primary, Secondary)	Level of Involvement in OMW	Interest in OMW Primitive Need
PEO Unmanned and Small Combatants (USC)	Internal	Secondary	Involved with any shipbuilding related to OMW including: mine laying, unmanned systems and communication systems. Littoral water systems focusing in OMW are also completed by this stakeholder.	Interested in capabilities assessments and recommendations for enhancements to shipboard, deployable vehicles. Interested in developing the highest value Mine Warfare systems possible.
Personnel: Navy and Marines	Internal	Secondary	Operators of UUV and UAV systems for the deployment, engagement, loiter, recovery, and relocation of minefields.	Interested in the best practices needed to deploy and maintain offensive minefields.
PMS 340: Naval Special Warfare Program Office	Internal	Secondary	Priorities include developing the high-level initial system development and procedures for Naval Special Warfare Operations.	Interested in the feasibility of outfitting underwater and surface ships with UAV and UUV compatibilities so that UUV and UAVs can accomplish missions.

Stakeholders	Classification (Project, Internal, 1st, 2nd, Boundary)	Type Prioritization (Primary, Secondary)	Level of Involvement in OMW	Interest in OMW Primitive Need
PMS 406: Unmanned Systems Program Office	Internal	Secondary	Oversees programmatic development of offensive mining systems specifically regarding the use of UAV and UUV development.	Interested in developing the disparate systems that allow for UUV and UAV technology to interact with surface and underwater ships but with a heavy focused on the unmanned vehicle systems.
PMS 495: Mine Warfare Systems	Internal	Secondary	PMS 495 focuses on the fielding, in-service support, development of all aspects of mine warfare. For our project purposes they are the point of contact for OMW.	Interested in developing the highest value Mine Warfare systems possible.
N95 (Expeditionary Warfare)	1st Order	Secondary	N95 develop the system requirements regarding naval missions centered around the use of OMW. Additionally, they shall develop the baseline characteristics and structures needed to support OMW compatibility on surface and underwater ships.	Interested in capabilities assessments and recommendations for enhancements to shipboard, deployable vehicles.

Stakeholders	Classification (Project, Internal, 1st, 2nd, Boundary)	Type Prioritization (Primary, Secondary)	Level of Involvement in OMW	Interest in OMW Primitive Need
Submarine Leadership Commander Submarine Force (CSF) N97(Undersea Warfare) PEO Subs	1st Order	Secondary	Responsible for development of future force capabilities by defining the future role of undersea forces in operations and warfighting; determining platform, systems, payload, people and posture requirements; and translating requirements into decisions, policy and funding.	Interested in developing improvements to the AUWS current design, assuring access to the maritime battlespace, autonomy and unmanned systems.

APPENDIX B. REQUIREMENTS SUMMARY

In addition to the functions described previously in the functional hierarchy and evaluation measures, there are two areas of non-functional requirements that will further define the overall system operation and support the high-level operational concept. These areas are command and control (commonly referred to as C2), and unmanned vehicle integration. This section will describe the concepts of C2 and unmanned integration and add several non-functional requirements and constraints that, along with the functions described in previous sections, will guide the design and development processes.

A. COMMAND AND CONTROL

Central to the operational concept of offensive mine warfare, as is the case with other areas of naval warfare, is command and control. The ability to deploy, recover, and use offensive mines is only as effective as the command and control measures put in place to provide warfare commanders with the same operational control of mines as current offensive weapons systems. Naval C2 requires operational autonomy since Naval assets commonly find themselves operating independently or with limited support. Offensive mines offer a unique and effective means of expanding the ability of naval forces to expand their ability to control the battlespace to far beyond current C2 capabilities by providing a stand-alone, autonomous weapons and intelligence-gathering asset, which can effectively deter or severely limit the operational capabilities of opposition forces. As CDR T. Michael Cashman wrote in Striking first—Mine Warfare Goes on the Offensive, “the physical and psychological impact of minefields, regardless of the actual number of mines or their sophistication, tends to be viewed as a serious danger and often results in reluctance on the part of naval combatants and merchant vessels to challenge them” (Cashman 2002). It is the intent of this project to provide the Navy with an operational concept that offers warfare commanders an effective tool with which to exercise C2 in a new way, and to increase their battlespace control ability via force-multiplication and autonomous area denial.

Communication, sometimes referred to as the “third C” of C2, is essential for utilization of operational assets. Because of its autonomous nature, the offensive mine

subsystems developed herein—the mines, delivery/recovery vehicles, and operating assets—must be able to communicate via established, secure, and versatile communications networks in order to fully realize the operational concept. Therefore, the system developed here will conform to the following requirements:

- All autonomous subsystems (mines and delivery/recovery UAVs/UUVs) shall integrate with existing communications systems (e.g. VHF/UHF radios and Link 16).
- All autonomous subsystems shall meet status reporting requirements as described in the previous functional hierarchy.
- All autonomous subsystems shall be able to switch control between available friendly assets as required by warfare commanders using available communications networks.

B. UNMANNED INTEGRATION

In order for naval commanders to exercise C2 in an effective and autonomous way, the operational concept generated by this project shall include the use of unmanned systems to deploy, recover, and relocate offensive mines. Unmanned systems provide flexibility and autonomy required to fully realize the intent of an offensive mine warfare concept that effectively controls the battlespace. In a Naval Research Advisory Committee report from 2000, it was stated:

> "… (unmanned vehicles) (UVs) have an increasingly important role in the MCM mission, and that Naval Forces will therefore require a family of UVs and sensor systems to provide end-to-end capability over the broad littoral environment. The vehicles will need to be clandestine, affordable, and expendable" (Naval Research Advisory Committee 2000, 3).

While the aforementioned report was concerned with mine countermeasure (MCM) systems, the idea can just as easily be applied to offensive mine systems. A "clandestine, affordable, and expendable" mine delivery and recovery system is a cornerstone of any viable offensive mine concept, and may require the development of new systems. While this project will not provide a system design for a specific UUV or UAV, it will provide

an overall system architecture and functional requirements that will aid future development efforts. To this end, the operational concept developed here shall conform to the following requirements:

- The system shall utilize both unmanned aerial vehicles (UAVs) and unmanned undersea vehicles (UUVs) to execute the deployment, recovery, and relocation functions described in the functional hierarchy.
- The UAVs and UUVs in the system shall integrate with current and near-future Naval assets in regards to communication and delivery methods.
- To maintain cost-effectiveness, the UUVs and UAVs shall utilize commercial-off-the-shelf (COTS) or existing platforms for delivery/recovery/relocation functions to the maximum extent possible.

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APPENDIX C. SIMULATION ASSUMPTIONS

This appendix is a reference for assumptions that were made when designing and testing the Offensive Mine Warfare simulation.

Assumptions:

1. When a UUV/UAV fails it is considered to fail at the location of the minefield and has the ability to commute back to the deployment point.
2. When deploying the UUV/UAV it is assumed that they are deployed at the same time and commute at the same speed. Once they are finished deploying assets, they return at the same speed and time regardless of how many mines they are carrying.
3. The same concept goes for maintenance, they are all assumed to take the same amount of maintenance time and maintenance is started simultaneously.
4. If the number of mines for mine1 is larger than the number of mines for mine2, and vice versa, the mines placed in the second row will fill in the empty spaces from left to right until the mine2 resources are depleted. Once that occurs the rest of the minefield is considered open space in row2.
5. Each index of the minefield is calculated by getting the percentage of the max engagement / length of minefield and then converted to an array
6. Each hostile contact is considered to instantaneously appear on the minefield at a random location.
7. If a mine detonates, it is assumed that it is automatically replaced before the next contact enters the minefield.
8. The time to conduct maintenance, the probability to kill and probability to detonate are all normal distributed variables that have a set mean and standard deviation.

9. Max engagements and reliabilities of each mine will not be equal because it is assumed that they are different mines and do not have the same properties.

10. Sea state and bathymetry are set on a scale from one to ten. For sea state, one being calm water and no wind and ten being hurricane conditions. For bathymetry, one being flat, solid bottom and ten being cavernous with varying elevations.

11. If the number of mines for n1 and n2 are equal, and the last mine in row 2 has an engagement range that is bigger than the open space in row1, the indexes for that engagement range are shrunk to ensure the indexes for row1 and row2 match.

SUPPLEMENTAL. MATLAB CODE

Files for inputs, simulation and analysis can be viewed using MATLAB 2019. Files include:

- Supplemental 1: getInputs_Final.m
- Supplemental 2: launchOMW_v6_Final.m
- Supplemental 3: Scenario1Plots.m
- Supplemental 4: Scenario2Plots.m

To retrieve the files, contact the Dudley Knox Library at the Naval Postgraduate School, https://library.nps.edu/.

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